Oct 2'51 J

Volume 21 SEPTEMBER, 1951 Number 3

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

« CONTENTS »

Stages of textural maturity in sedimentary rocks . . *Robert L. Folk* 127

Depth of disturbance of sand on sea beaches by waves . . . . . *C. A. M. King* 131

Pre-Cambrian sinuous mud cracks from Idaho and Montana . . . . . *Harry E. Wheeler and James J. Quinlan* 141

Playa sediments of Rosamond Dry Lake, California . . . . . *Warren B. Hamilton* 147

The sediments of Lake Elsinore, Riverside County, California . . . . *John F. Mann, Jr.* 151

Grain orientation in sands and sandstones . . . . . *W. Schwarzacher* 162

A rapid substitute for textural analysis . . . . . *Irving Sherman* 173

Derivation of a size-frequency curve from the cumulative curve . . . *James Bush* 178

DISCUSSION

Some remarks on the mineral epidote in connection with the loess problem . . . . . *F. F. F. E. van Rummelen* 183

Remarks on "Beach sands of the Mediterranean Coast of Egypt" by Mohamed E. Hilmy . . . . . *N. M. Shukri* 185

Journal of Sedimentary Petrology

J. L. HOUGH, EDITOR
University of Illinois
Urbana, Illinois

W. H. TWENHOFEL, Consulting Editor
Orlando, Florida

ASSOCIATE EDITORS

W. C. KRUMBEIN
Northwestern University
Evanston, Illinois

K. O. EMERY
University of Southern California
Los Angeles, California

HENRY B. MILNER
London, England

CLARENCE S. ROSS
Washington, D.C.

RALPH E. GRIM
University of Illinois
Urbana, Illinois

R. DANA RUSSELL
U. S. Navy Electronics Laboratory
University of California
San Diego, California

The *Journal of Sedimentary Petrology* is published by the Society of Economic Paleontologists and Mineralogists, a division of The American Association of Petroleum Geologists. Numbers are issued in March, June, September and December.

The subscription price of the *Journal of Sedimentary Petrology* is $5.00 per year prepaid to addresses in the United States.

Single numbers, $1.75 each ($1.35 to members).

Postage is charged extra for all other countries: 40 cents on annual subscriptions (*total* $5.40).

The *Journal* will furnish reprints at cost. Orders should accompany corrected galley proof.

Communications about the *Journal*, advertising, subscriptions, rates, memberships, change of address, and non-receipt of preceding number should be addressed to Society of Economic Paleontologists and Mineralogists, P.O. Box 979, Tulsa, Oklahoma. Claims for non-receipt of preceding numbers must be sent in within three months of the date of publication in order to be filled gratis.

Communications in regard to manuscripts and purely editorial matters should be addressed to J. L. Hough, Journal of Sedimentary Petrology, University of Illinois, Urbana, Illinois.

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN

Volume 21 SEPTEMBER, 1951 Number 3

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

CONTENTS

Stages of textural maturity in sedimentary rocks.....*Robert L. Folk* 127

Depth of disturbance of sand on sea beaches by waves.....*C. A. M. King* 131

Pre-Cambrian sinuous mud cracks from Idaho and Montana.....*Harry E. Wheeler and James J. Quinlan* 141

Playa sediments of Rosamond Dry Lake, California.....*Warren B. Hamilton* 147

The sediments of Lake Elsinore, Riverside County, California.....*John F. Mann, Jr.* 151

Grain orientation in sands and sandstones.....*W. Schwarzacher* 162

A rapid substitute for textural analysis.....*Irving Sherman* 173

Derivation of a size-frequency curve from the cumulative curve.....*James Bush* 178

DISCUSSION

Some remarks on the mineral epidote in connection with the loess problem.....*F. F. F. E. van Rummelen* 183

Remarks on "Beach sands of the Mediterranean Coast of Egypt" by Mohamed E. Hilmy.....*N. M. Shukri* 185

NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among papers to appear in forthcoming issues of the *Journal* are the following:

Microfossils as environment indicators in marine shales. By Samuel P. Ellison, Jr.

The depositional environment of red and green shales. By Ralph E. Grim.

Lithology of the limestones at LeGrand, Iowa. By Ralph W. Lawson.

Beach sand at Los Ojos de Agua de San Telmo, Michoacán, Mexico. By Fred M. Bullard and Richard A. Mills.

The occurrence and derivation of an augite rich beach sand, Granada, B.W.I. By H. S. Bennett and P. Martin-Kaye.

Pebbles from a pothole: a study in shape and roundness. By Dorothy Carroll.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 3, PP. 127–130
FIG. 1, SEPTEMBER, 1951

STAGES OF TEXTURAL MATURITY IN SEDIMENTARY ROCKS

ROBERT L. FOLK
The Pennsylvania State College

ABSTRACT

Four stages of textural maturity in sediments are defined by the occurrence of three sequential events (1) removal of clays, (2) sorting of the sand fraction, and (3) attainment of high roundness. A binomial terminology is introduced wherein the term denoting textural maturity is prefixed to the rock-composition name, obtained from the mineralogy of the silt-sand-gravel portion (e.g., "submature graywacke").

INTRODUCTION

Sediments are characterized by two fundamental properties, mineral composition and texture (Krynine, 1948). It is desirable to include both these properties when determining a name for a particular rock. Texture may be considered from two points of view: (1) the variation in grain size (average and range); and (2) the textural maturity of the rock as expressed in clay content, sorting, and roundness. The broad concept of "maturity" was introduced by Pettijohn (1949) and Plumley (1948) to describe the approach of a sediment to the most inert end state possible, through the operation of both physical processes (tending to produce a perfectly sorted and rounded sediment) and chemical processes (tending to produce a sediment containing only the most stable minerals). The present paper concerns only *textural* maturity; four distinct stages are defined, with the suitable term expressing textural maturity being prefixed to the compositional name of the rock (e.g., "submature graywacke").

The need for such a binomial terminology arises due to the fact that textural maturity and mineral composition are capable of much independent variation, although, of course, ultimately affecting one another. For example, an arkose with a composition of 70 per cent quartz and 30 per cent feldspar may show all degrees of textural maturity from an angular, poorly sorted fanglomerate to the perfectly rounded and sorted sands of the Cambro-Ordovician of Pennsylvania. It is obviously unsatisfactory to call these two contrasting rocks by the unqualified term "arkose." Similarly, perfectly rounded and sorted sediments may consist entirely of quartz, or may contain in addition sizeable quantities of feldspar, resistant metamorphic rock fragments, etc. To circumvent these difficulties a twofold terminology, embracing both mineral composition and textural maturity, is here introduced.

DEFINITION OF THE FOUR STAGES OF TEXTURAL MATURITY

The passage from an initial clayey, poorly sorted, angular sediment to a completely matured, rounded and sorted sand is marked by three easily recognizable steps, which take place in constant sequential order in response to the total input of modifying energy. These three steps are, in the order of their occurrence: (1) removal of clay, requiring least energy; (2) attainment of good sorting in the non-clay portion, requiring more energy; and (3) rounding of the grains, requiring most energy. The four stages of textural maturity, described below, are delimited by the occurrence of these three steps.

I. Immature stage. Sediment contains considerable clay and fine mica, the non-clay portion is itself poorly sorted,

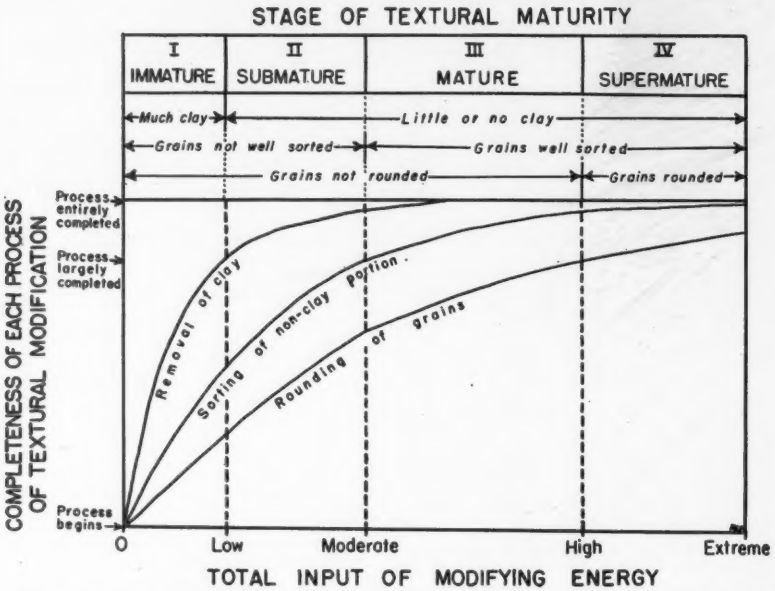


FIG. 1.—Relative completeness of each process of textural modification (winnowing, sorting, and rounding) as a function of the amount of energy expended. When a given process is largely completed, the rock passes from one stage into the next one, as shown by the broken vertical lines.

and the grains are angular. When the clay is winnowed out, stage II is attained.

II. Submature stage. Sediment contains very little or no clay, but the non-clay portion (silt, sand, or gravel) is still in itself poorly sorted and the grains are angular. As soon as the sediment becomes well-sorted, stage III is attained.

III. Mature stage. Sediment contains no clay and is well-sorted, but the grains are still subangular. When the grains become rounded stage IV is attained.

IV. Supermature stage. Sediment contains no clay, is well-sorted, and the grains are rounded. This is the ultimate textural stage and no further modification is possible in this cycle.

The four stages are depicted in the qualitative diagram (fig. 1), which shows the completeness of each process of textural modification (winnowing, sorting, and rounding) as a function of the amount of energy expended. This diagram shows that, although all processes begin operation simultaneously, some require a much greater energy input and, therefore, do not reach practical completion until much later. The fact that the processes are completed at different times provides the basis for the classification.

Exact definitions are painful to construct, cumbersome to follow, and invite argument because of their necessarily arbitrary nature; yet unless exact definitions are attempted, ambiguity and loose usage inevitably follow. Therefore, to avoid misunderstanding as to just what is meant by "considerable clay," "well-sorted," and "rounded," the following

precise definitions of stage limits are proposed:

Stage I passes into stage II when the sediment comes to contain less than 5 per cent detrital clay; sericite and fine-grained micas less than 0.03 mm in length are included as "clay" when used in this sense.

Stage II passes into stage III when the sediment attains an S_o value (Trask's sorting coefficient) of less than 1.30. This corresponds roughly to a spread of 1.2 phi units between the 10th and 90th percentiles; and in thin section, approximately two-thirds of the grains occur within a diameter range of one phi unit.

Stage III passes into stage IV when the quartz grains of sand size attain an average roundness of 0.50 or better, using the visual comparison chart of Krumbein (1941).

THE CONCEPT OF MATURITY APPLIED TO PELITES

Inasmuch as all shales contain clay, they would all be classed as immature rocks if the definitions of the stages of textural maturity given previously were followed. However, when an initial, unmodified sediment has the clay winnowed out of it and passes from an immature to a submature sandstone, the clay must go somewhere; therefore, the finer-grained shales should generally represent the deeper-water complement of more mature sandstones and conglomerates nearer shore. The degree of splitting of clay versus sand depends on the amount of modifying energy applied to the initial sediment, hence is a function of the rate of subsidence. When subsidence is rapid, little winnowing takes place, and the deposits consist of poorly differentiated sandy or silty mudstones or shales, plus very clayey immature sandstones. When subsidence is slow, allowing ample time for textural modification, the deposits are well-differentiated and consist of relatively well-sorted clay shales or only slightly silty shales plus mature, well-sorted sandstones.

Therefore, since mature sandstones accompany texturally finer shales, it is proposed that pelites consisting predominantly of clay-size material, with a very subordinate amount of slit and no sand, be termed "mature." Pelites consisting of subequal proportions of silt and clay together with small amounts of sand are "immature"; and pelites composed largely of clay but with a moderate amount of silt are "submature."

TEXTURAL INVERSION

Although the above four stages generally follow in strict sequential order, occasional rocks show an inversion of the textural stage; e.g., have well-rounded grains embedded in an abundant clay matrix, or have well-rounded but poorly sorted grains. In these instances, special conditions are indicated, such as the presence of second-cycle sedimentary grains which inherited their shape from a previous cycle but whose sorting is a response to conditions of the final cycle. In such cases, the adjectival term applied when naming the rock is that of the lowest stage of textural maturity represented.

LINKAGE OF COMPOSITION AND TEXTURE IN A BINARY TERMINOLOGY

The main name of a sedimentary rock should be based on mineral composition, and should not be influenced by such variables as texture, grain size, amount of authigenesis, or the presence of special structures. Terrigenous sediments may be conveniently classified on the basis of a tetrahedron, with four poles representing characteristic mineral assemblages:[1] (1) the stable, silica group (quartz and chert): (2) the igneous group (feldspars and igneous rock fragments); (3) the metamorphic group (metamorphic rock fragments and micas); and (4) the clay group.

Despite some overlap (e.g., micas may come from both igneous granites and metamorphic schists), the first three of

[1] Slightly modified from the three poles of Krynine (1948).

the above polar groups typically indicate derivation from three major source terranes, respectively sedimentary, igneous, and metamorphic (Krynine, 1944). However, the clay group (occupying the fourth pole) generally does not indicate a characteristic source terrane, and in addition is subject to two factors tending to diminish its compositional significance; (1) its presence in the sediment is almost entirely a function of texture, and (2) it is prone to extensive authigenesis, which may completely alter its original mineralogy. Thus, clay may be regarded as a dominantly textural diluent of the tetrahedron, and if the clay pole is eliminated the tetrahedron reduces to a composition triangle similar to that employed by Krynine (1948, fig. 4). The main rock name, therefore, depends on the mineral composition of the silt-sand-gravel fraction, and the presence of clay is left to be described in the textural portion of the name.

When the main rock name has been determined, the word denoting the stage of textural maturity is prefixed to it, as "submature arkose," "mature quartzite," etc. There is one exception to this rule: inasmuch as the arkose, impure arkose, feldspathic graywacke (the graywacke of Pettijohn (1949) or the high-rank graywacke of Krynine), and subgraywacke (low-rank or common graywacke of Krynine), are most commonly in the immature state, the word "immature" is omitted in these four rocks. Thus, when the term "arkose" is used alone, "immature arkose" is to be understood.

ADDITION OF A TERM DENOTING GRAIN SIZE

For combining the three variables, grain size, textural maturity, and mineral composition, the writer has found the following scheme useful. First, the grain-size term is applied, using the nomenclature of Krynine (1948) or any other textural classification. This is separated by a colon from the textural-maturity and rock-composition terms, as in "pebbly sandstone: mature quartzite," or "sandy boulder conglomerate: submature arkose," following the general formula (grain size): (textural maturity) (rock composition).

In this way, three important parameters of the sedimentary rock are embraced in one term: (1) mineral composition, a function of lithology and hence tectonic state of the source area (Krynine, 1943); (2) grain size, a function of the proximity and topographic relief of the source; and (3) textural maturity, a function of the amount of physical modification by agents at the site of deposition, and, therefore, an index of the rate of subsidence of the basin. It is hoped that this procedure, although producing a somewhat lengthy name, will add to the precision of sedimentary rock descriptions.

REFERENCES

KRUMBEIN, W. C., *1941*. Measurement and geological significance of shape and roundness of sedimentary rock particles: *Jour. Sedimentary Petrology* vol. 11, pp. 64–72.

KRYNINE, P. D., *1943*. Diastrophism and the evolution of sedimentary rocks (outline of lecture): Distinguished Lecture Comm. of Am. Assoc. Petroleum Geologists.

———, *1944*. Basic Sedimentology: unpubl. syllabus, The Pennsylvania State College.

———, *1948*. The megascopic study and field classification of sedimentary rocks: *Jour. Geology*, vol. 56, pp. 130–165.

PETTIJOHN, F. J., *1949*. *Sedimentary Rocks:* Harper and Brothers, New York, 526 pp.

PLUMLEY, W. J., *1948*. Black Hills terrace gravels: a study in sediment transport: *Jour. Geology*, vol. 56, pp. 526–577.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 3, PP. 131–140
FIGS. 1–7, SEPTEMBER, 1951

DEPTH OF DISTURBANCE OF SAND ON SEA BEACHES BY WAVES

C. A. M. KING
University of Nottingham, Nottingham, England

ABSTRACT

Experiments which were made to determine the depth of disturbance of beach sand by waves are discussed. The method of the experiments, which were made with dyed sand, is described. A significant correlation was found between the depth of disturbance of the sand and the wave height, and the results have been analyzed statistically. The depth of sand disturbance was in general very small, but it was found to increase with increasing wave height and energy. The disturbance was found to be greatest in the relatively shallow water at and inside the breakpoint of the waves. It was found that the depth of disturbance was greater as the sand became coarser. The significance of the results of the experiment is discussed briefly.

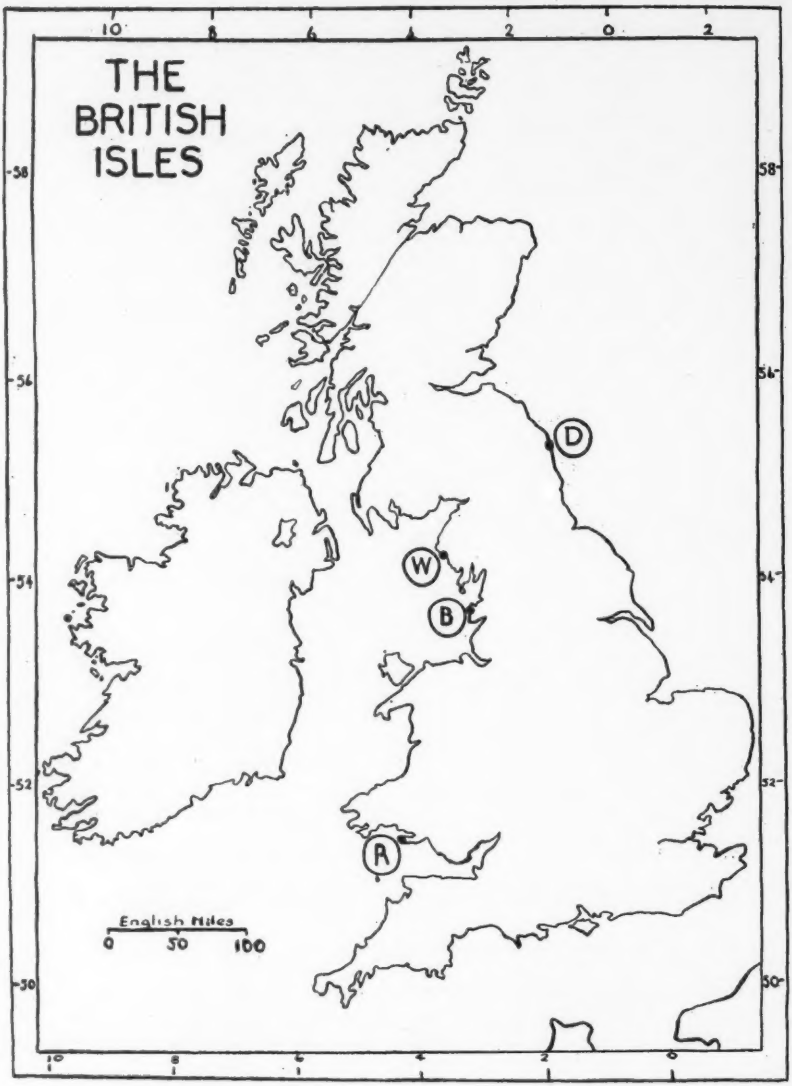
INTRODUCTION

The action of waves on the sand of a beach is a subject about which relatively few precise quantitative data are available. This is mainly due to the difficulty of observing the actual movement of the sand under wave action on a beach. It is thought, therefore, that a short description of experiments carried out on several sandy beaches round the coast of England, to determine one aspect of sand movement, might be of interest. The location of the beaches studied is shown on figure 1. The experiments were made to determine the depth to which waves disturb the sand on a beach, and to correlate this depth with the different wave characteristics and other factors which influence the depth of disturbance.

METHOD OF EXPERIMENT

A small quantity of sand was taken from the beach where the experiment was to be carried out. This sand was then dyed by using ordinary waterproof drawing ink. The color was purple as this formed a strong contrast to the normal sand color. The sand was washed after dying to ensure that no color ran to the adjoining sand. At low tide a suitable site on the beach was selected, near the surveyed profile. A vertical face, 6 to 9 inches high, was cut in the sand at this point, colored sand was filled into a groove on this face, to a depth of several inches, the hole was then filled in and carefully smoothed over. It was now necessary to mark the site of the colored sand so that it could be found again; this was done by means of thin pegs, about one-quarter inch in diameter and 1½ to 2 feet long. They were placed so that the colored sand lay on the straight line joining them and at a known distance from either. The pegs served the additional purpose of enabling the change in actual elevation of the sand surface in the area of the experiment to be measured. The length of the peg above the sand surface, normally about 6 inches, was noted before the experiment and any change in elevation of the sand surface could be found by measuring the peg afterwards.

Thin pegs were used for the experiment and the dyed sand was placed at least 1 foot from them, so that the scour caused by an object on the beach would not affect the result. Large objects such as boulders on a beach cause considerable wave scour which leads to the formation of a deep pool round the object, if it is greater than a certain size. The waves, particularly the back-wash, scour the sand from under and round the obstacle. It was noted that the stones about 1 square foot in area to which the buoys,



D. DRURIDGE W. WHITBECK

B. BLACKPOOL R. RHOSSILI

FIG. 1.—Map to show location of beaches on which observations were made.

mentioned later, were moored became entirely buried in the sand after one tide had risen and fallen over the area. Thus a large object on the beach will greatly increase the amount of sand disturbance in its vicinity.

After the tide had risen and fallen again the position of the colored sand was found with reference to the pegs and the exact site marked. This was then carefully undermined from below, until the bottom of the purple column of sand was found. This was then followed up until it came to an abrupt end. The distance between this point, which was normally clearly defined, to the smooth sand surface was measured to the nearest millimeter. This measurement gives the disturbance depth of the sand under those particular wave conditions and other factors; the sand above the level at which the purple column stops has been scattered and dispersed by the waves, the purple sand below this level has not been affected by wave action. This result must, however, be used with a certain amount of caution. One factor which is liable to make the result misleading is the actual change in elevation of the sand surface in the area of the experiment. The amount of this change can be measured on the pegs, but it is impossible to know whether the accretion or erosion of sand took place before or after the maximum disturbance of the sand by the waves. If it took place before the maximum disturbance, the amount of disturbance measured will be correct; but if it took place afterwards, the depth of disturbance will be too great if accretion has taken place and too small if erosion has taken place. To overcome this difficulty, where possible observations were taken where the change in sand elevation was small or nil. This was not always possible and the scatter of the points on the graphs may be partly explained by this factor.

The depth of water over the dyed sand at high tide can be ascertained from the position of the sand on the surveyed profile of the beach and the predicted or observed tide height. The sand was placed at different positions along the profile so that the depth of water at high tide varied. This was done so that it might be possible, under any given wave conditions, to determine the depth at which the maximum disturbance of sand took place and to correlate this depth with the different parts of the wave profile. Colored sand was emplaced in the beach so that at high tide the one in shallowest water would be under the action of the swash of the waves only. Another was placed so that it would lie under the break-point of the waves at high water and one was placed so that it would lie well outside the break-point of the waves at high tide in about 20 feet of water. It is evident that it is impossible by this method to measure the depth of disturbance in water that is deeper than that in which the maximum disturbance takes place. As the tide rises and falls each dyed sand site in turn comes under the action of the waves, first the swash, then the break-point, and the deeper water outside the break-point. Thus if the maximum disturbance is in shallow water it is impossible to measure the disturbance in deep water.

RESULTS OF THE EXPERIMENT

Depth of Maximum Disturbance

Experiments were made at Rhossili to determine the place in relation to the wave break-point were the maximum disturbance took place. Rhossili Bay, at the western end of the Gower Peninsula in South Wales (fig. 1) has a wide smooth sand beach, facing due west, so that it is open to the long swells coming in from the Atlantic. The beach is flat, having an average gradient of 1 in 80, and a width at low spring tide of nearly 2,400 feet. (See fig. 2)

The tidal range is considerable, being nearly 26 feet at spring tide, and so it was possible to place the samples of colored sand for the purpose of this experiment so that at high tide the water

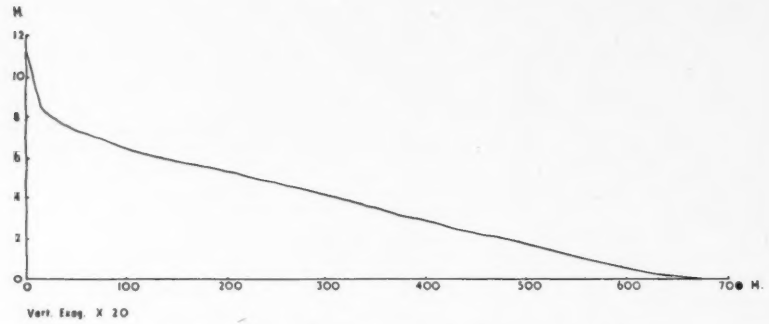


FIG. 2.—Profile of Rhossili beach surveyed March 15, 1949.

was about 20 feet deep. Dyed sand was placed on this beach so that at high water one sample was under the swash of the waves, another near the break-point and a third in deep water, outside the break-point.

The results obtained from this experiment indicated that, as the three results were similar, the depth of disturbance in only a few feet of water under the swash of the waves, was as great as that under the break-point or in deep water. It is perhaps strange that the disturbance depth under the break-point is not greater than that under the swash, as the maximum disturbance would be expected to occur under the break-point. That the disturbance is as great under the swash on Rhossili beach may be explained by the type of breaker associated with the beach. The very flat beach together with the long crested swell, which normally comes in from the Atlantic, may account for the type of breaker. The waves do not destroy all their energy and form in one place, but continue to move landwards with foaming crests until they eventually lose height at the edge of the sea and become swash. A broken wave of this type is usually called a surf wave and on a flat beach of this type several surf waves may be seen moving landwards simultaneously. The number of surf waves on any given beach gradient will depend on the wave height and length; on Rhossili beach it varies from one or two rows of surf in calm weather to seven or eight with high waves and strong onshore winds which cause the wave to break farther from the shore. The exact motion of the water and the sand under surf wave action has not been able to be observed, but from this experiment it does appear that the amount of disturbance of the sea bed does not diminish appreciably until the water becomes extremely shallow. That the disturbance depth is not greater in 20 feet of water than it is at the break-point is not surprising, as it is well known that the wave motion decreases very rapidly in intensity with increasing depth. The orbital velocities of particle movement in waves in deep water decreases in geometrical ratio, where the depth increase is in arithmetical ratio. Although this does not apply exactly to waves in shallow water, it does indicate that at a depth of 20 feet with relatively small waves the bottom would probably hardly be disturbed at all and certainly the turbulence, even with the long swells typical of this beach, would be small at such a depth.

The conclusion is reached, therefore, that the depth of disturbance is at a maximum in relatively shallow water, at and inside the break-point, on gradients typical of normal sand beaches, which

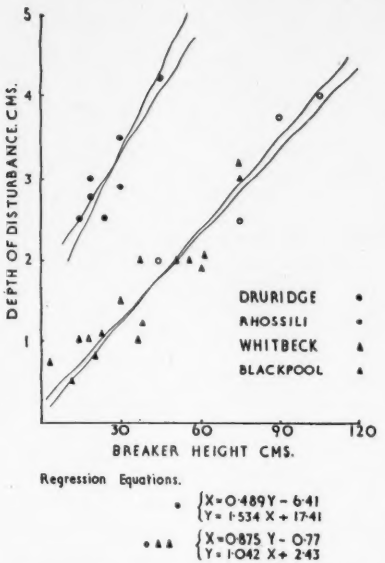


FIG. 3.—Graph to show correlation of disturbance depth of sand with wave height at break-point. Observations made at Blackpool, Rhossili, Whitbeck and Druridge in 1947.

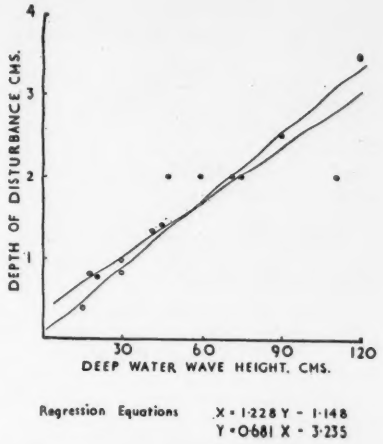


FIG. 4.—Graph to show correlation of disturbance depth of sand with deep-water wave height. Observations made at Rhossili in 1948 and 1949.

are relatively flat. In this area the turbulence is greatest and here, by far, the greatest amount of sand movement takes place.

The Effect of Wave Height

The variations in the depth of disturbance of the sand are related to the wave characteristics acting during the period that the dyed sand was under the influence of broken waves. The measured disturbance depths were plotted against the different wave characteristics to determine which are most important in explaining the different results. It was found that, on all beaches on which observations were made, there was a close correlation between wave height and depth of disturbance. The relation between the two variables appears to be approximately linear. The depth of disturbance is of the order of 1 centimeter for each foot of wave height at the break-point, thus a 3-foot breaker will disturb the sand to a depth of about 3 centimeters.

The connection between the two factors is shown in figures 3 and 4. Figure 3 shows the correlation between the depth of disturbance and the breaker height from data obtained during field work in 1947 on a variety of beaches. It will be seen that three of the sand samples shown in the graph correlate well with each other. These are the sands of Blackpool, Whitbeck and Rhossili, whereas the fourth beach, Druridge Bay (see fig. 1 for localities of beaches), shows a consistently greater disturbance depth for the same wave height. The correlation coefficient for the first three localities is $r-0.9548$, and for the Druridge observations the correlation coefficient is $r-0.859$. The reason for the greater disturbance depth at Druridge will be pointed out in a later paragraph. The depth of disturbance shows a linear increase with wave height increase. In this graph the wave heights

were estimated in some cases and the scatter of points may partly be due to this cause.

In figure 4 observations made at Rhossili in 1948 and 1949 are shown. The correlation coefficient of these observations is 0.9149. The deep-water wave height is used in this graph and, apart from one point, the correlation is reasonably close, showing a linear relationship. The wave heights used in this graph were measured by a method devised by W. W. Williams, and checks showed it to be reasonably accurate.

At low water buoys were moored on the beach so that at high tide they would be floating in a known depth of water. Spherical buoys painted yellow and black were used. At high water the buoys were sighted through a theodolite from the top of the cliff. The angular distance between the wave crest and trough could then be measured. This is a measure of the wave height. An average of five or more wave crests and troughs were measured. The lower mean value was subtracted from the higher, the result giving the angular distance to the nearest second of arc between the wave crest and trough. This must be converted into linear measure before it can be used. This was done at low tide, when a 14-foot staff was held on the site near which the buoy floated at high tide. The intercept on the staff was measured and from this the value of 1 foot in minutes and seconds of arc could be calculated. Three buoys were used, the outermost covered by about 20 feet of water, the middle by 10 to 16 feet, and the inner one by 2 to 6 feet, according to the height of the tide. The readings taken on the outer buoy were very often the same as those recorded on the middle buoy, and this figure was taken as the deep-water wave height. It is not a deep-water wave height in the strict sense of the term, which implies that the water depth should be at least equal to half the wave length; a depth of about 250 feet for the average wave length of 500 feet recorded on this beach. Rapid increase of wave height does not take place, however, till very near the break-point of the waves so that the measured wave height probably approximates fairly closely to the true deep-water wave height. The readings on the inner buoy were checked with those made on a graduated pole fixed in a similar depth of water and the two measurements agreed well, thus giving confidence in this method of measuring wave height.

It may, therefore, be concluded that wave height is an important factor affecting the depth to which waves disturb the sand. The depth of water at the break-point depends on the wave height and the amount of turbulence in the shallower water, thus as the wave height increases so the depth of disturbance increases in an approximately linear proportion.

The Effect of Wave Energy

Wave energy is a function of wave height and wave length. It is proportional to the square of the wave height and one power of the wave length. The equation used to give wave energy was $E = 0.64\ w\ H^2T^2$, where E is the wave energy in foot-lbs. for 1 foot of wave crest over a distance equal to one wave length, w is the weight of 1 cubic foot of sea water in lbs., H is the wave height in deep water in feet, and T is the wave period in seconds. As the square of the wave height is in the equation, it is natural that this factor should exert a large influence on the wave energy. Therefore, because the wave height correlates with the disturbance depth, it is to be expected that the wave energy will give a similar correlation. This is shown in figure 5. This graph is plotted on semi-logarithmic paper because the increase of wave energy is very rapid as the formula includes the square of the wave height and period. The same observations are plotted as in the previous figures. The correlation of the variables is still apparent although there is a considerable scatter of the points. The great energy of the waves recorded at Rhossili is due

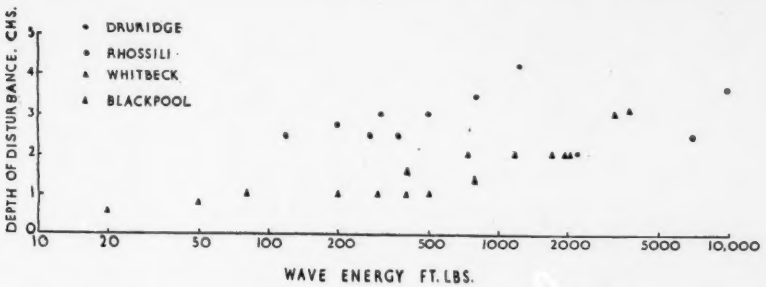


FIG. 5.—Graph to show correlation of disturbance depth of sand with wave energy. Observations made at Blackpool, Rhossili, Whitbeck, and Druridge.

to their great length, as this beach is open to the long Atlantic swell. The observations at Druridge again show a greater reaction to the wave energy, the depth of disturbance being greater for any given energy. The other three beaches show comparable depths of disturbance under similar wave conditions.

The correlation of disturbance depth with wave length was not at all close; therefore, it may be assumed that the wave height is the factor on which the depth of disturbance primarily depends. Also, it is the importance of wave height in a measurement of the wave energy which accounts for the correlation of the wave energy with the depth of disturbance, although the wave length or period may play a secondary part in determining the actual depth of disturbance on any one beach.

The Effect of Sand Size

It has been pointed out that the sand at Druridge Bay reacts to the waves more than the sands of the other three beaches on which observations were made. A reason for this may be found if the median diameters of the different sands are considered. The median diameters concerned are as follow:

Blackpool	0.22 mm
Rhossili	0.23 mm
Whitbeck	0.29 mm
Druridge	0.40 mm

The grading of the sand is shown in figure 6. Druridge sand is thus considerably coarser than the other three sands, all of which are relatively fine sands, particularly Blackpool and Rhossili which are nearly of the same grade. The coarse grade of the Druridge sand is the factor on which the greater depth of disturbance recorded on that beach depends. Figure 7 shows a profile of the beach at Druridge. A coarse sand allows water to percolate more readily; a steeper swash slope, therefore, results and on this steeper gradient the swash is more turbulent. It has been shown that it is in the swash zone that the maximum disturbance takes place. The waves break close inshore on a steep gradient of this type, so that the breaker and swash zones are narrow. The turbulence is concentrated in this narrow zone, and the sand is therefore disturbed to a greater depth on a steeper slope, which is the result of the coarser sand.

Although fewer layers of sand are probably disturbed on Druridge beach than on the fine sand beaches, the actual depth to which the disturbance penetrates is greater. Thus it may be concluded that the depth of disturbance depends partly on the median diameter of the sand concerned and that as the diameter increases so the depth to which any particular wave can disturb the sand increases. Thus it would be expected that the depth of disturbance would be

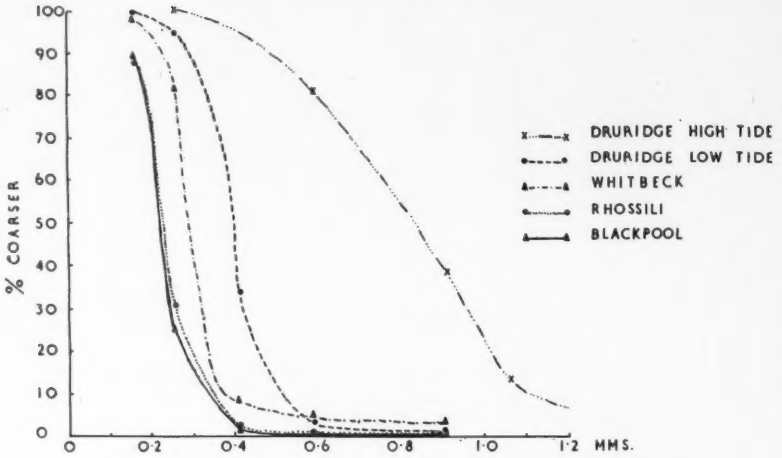


FIG. 6.—Graph to show grading of beach sand from Blackpool, Rhossili, Whitbeck, and Druridge.

greatest in shingle, where if only two or three layers of pebbles are moved the depth of disturbance would be greater than that on a fine sand beach. Fine mud should react even less than sand to the waves, but it is rare to find mud on a coast in any but very sheltered sites where the wave action would be very slight in any case.

SIGNIFICANCE OF THE EXPERIMENT: CONCLUSIONS

The experiment has shown that the depth to which sand is disturbed by the waves is very small under normal conditions on a relatively fine sand beach. The approximate value of 1 centimeter of disturbance depth for 1 foot of wave height at break-point appears to give a rough estimate of the depth of disturbance. The relationship is nearly linear and can, therefore, be extended to give the probable disturbance under any given wave height. Assuming a maximum wave height of 20 feet, which is rare close inshore, the corresponding depth of disturbance would be about 20 centimeters or about 8 inches. A more likely maximum depth of disturbance is probably of the order of 6 inches and the average under normal calm conditions is very much less, being about 1 or 2 inches or less. This result seems to hold for beaches in a variety of different situations, some of them like Rhossili face the open Atlantic, others, for instance Blackpool and Whitbeck, are confined to the waves generated in the limited fetch across the Irish Channel. This, of course, assumes that the actual change of sand elevation at the point of observation is negligible.

The depth at which this disturbance takes place is relatively small, as it has been shown that the waves disturb the sand most effectively at or inside their break-point. In deep water the depth of disturbance is probably very much reduced, because of the decrease in turbulence of the water as the depth increases. These results may be of interest in discussing the work of the sea on the coast and in interpreting the formation of such features as wave-cut benches. Johnson (1919) has suggested that the wave-cut bench is eroded by

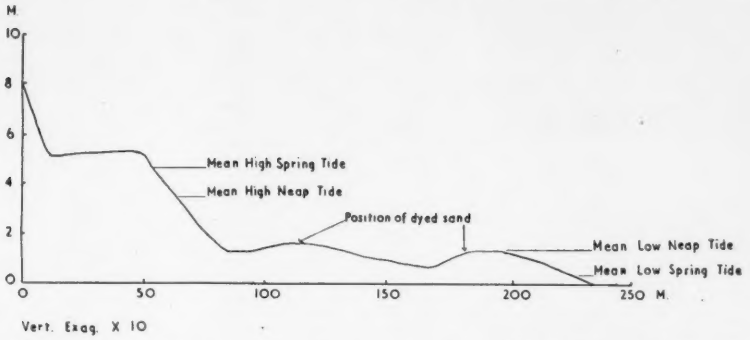


FIG. 7.—Profile of Druridge beach, surveyed August 7, 1947. Note steep gradient near high water level due to presence of coarser sand (0.84 mm median diameter) on the upper part of the beach.

the scouring action of beach material on the bench, in transit under wave action to deeper water. Johnson does not estimate the probable thickness of the beach material involved in this erosion of the bench, but from the results of this experiment it can be shown that the thickness of the sand on the bench would have to be very thin indeed, only a few inches if the sand were fine, if the bench is to be cut or be lowered by this method. From this it follows that the sand beaches normally found round the coasts protect the rocks beneath, as the sand is rarely sufficiently thin to be disturbed throughout its depth. The only conditions under which a wave-cut bench may be formed are found when beaches of loose material are lacking from that particular coast, or when all the sand is moved seawards from the beach by the destructive influence of severe storm waves thus exposing the rock bench beneath. The frequency with which this occurs depends on the exposure of the beach and the thickness of the sand deposit on it. It is probably very rare on thick sand beaches. When the bench is not covered with sand the waves can attack the cliffs directly and with the small amount of material derived from this work can effectively cut a wave eroded bench below the cliffs. On tidal beaches the bench is normally formed at a level which allows it to be exposed at the lower tides. A good example of such a bench is to be seen south of Worm's Head at the west end of the Gower Peninsula near Rhossili beach and on this bench there is no beach material at all.

Thus it follows that the presence of sand or shingle in the form of a beach has a protective effect on the rocks beneath, and as long as the beach material prevents the waves reaching the rocks, either the bench beneath or the cliffs behind, these cannot be attacked by marine erosion. Coast erosion can, therefore, only take place where the material is unable to accumulate. This occurs primarily at headlands, where the material is drifted away from these areas to the bays, or where longshore drifting of beach material removes an excess of material from the area, enabling the sea to reach the cliffs.

It has been shown that the depth of sand disturbance by waves on relatively fine sand beaches is small, but increases with increase of wave height and energy and as the sand becomes coarser. The waves disturb the sand most in the shallower water where they are broken. In deep water the disturbance is probably very much less. It has been observed

that when waves are breaking in 2 feet of water the sand is not moved to any great extent at a depth of 5 feet or more, although if ripples are present sand may be moved in small quantities from their crests by eddy action. Thus the conclusion is reached that waves cannot disturb the sand to great depths in deeper water, and that even in shallow water the depth of disturbance is extremely small.

REFERENCE

JOHNSON, D. W., *1919. Shore Processes and Shoreline Development:* John Wiley and Sons Inc., New York, 341 pp.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 3, PP. 141–146
FIGS. 1–5, SEPTEMBER, 1951

PRE-CAMBRIAN SINUOUS MUD CRACKS FROM IDAHO AND MONTANA

HARRY E. WHEELER AND JAMES J. QUINLAN
University of Washington and Sunshine Mining Company, Kellogg, Idaho

ABSTRACT

Sinuous traces lying in the troughs on the bedding surfaces of ripple-marked quartzites from the Belt group of the Coeur d'Alene Mountains in northern Idaho and the Big Belt Mountains in southwestern Montana are identified as mud cracks. Probable identity of these structures with those previously described as "trails" or "burrows" from the Huronian Ajibik quartzite of Michigan indicates that these "fossils" are also of mud crack origin.

INTRODUCTION

Mud cracks, which are typically of polygonal form, are common shallow-water features of sedimentary rocks of all geological ages. In addition to the frequently occurring hexagonal type, however, a few unusual patterns have been described, such as radiate (Kindle, 1926), rectangular (Shrock, 1940), and "incomplete" mud cracks (Fenton and Fenton, 1937). The mud cracks herein described are unusual in that nearly all are confined to the troughs of ripple marks, and that they describe sinuous curves, the X coordinates axes of which generally coincide with the axial trends of the troughs (fig. 1).

Immediately following our initial interest in this material Faul (1948) briefly mentions what appears to be the same phenomenon from the Ajibik quartzite of the Huronian of Michigan. In this and later accounts Faul (1949 and 1950) regards similar sinuous traces as fossil "trails" or "burrows."

Detailed study of the Idaho and Montana material has led to the present authors conclusion that the sinuous markings are mud crack fillings. On the basis of the remarkable similarity of occurrence and general character, together with the apparent identity of internal structure, we have little doubt as to the identity of the Michigan occurrence with those from the Northwest. Insofar as this identification is correct, another pre-Cambrian "fossil" is to be regarded as an inorganic structure.

COEUR D'ALENE OCCURRENCE

The sinuous markings were first observed on ripple-marked quartzite surfaces of float specimens from a talus slope of the Striped Peak formation on the south side of Striped Peak in the Coeur d'Alene Mountains, about 4 miles southwest of Wallace, Idaho. A single specimen which appeared to be in place was collected from near the mountain summit, the stratigraphic position of which lies approximately 500 feet above the base of the formation.

Ransome and Calkins (1908, p. 44) state that "The Striped Peak formation is composed of thin bedded rocks, including shales and quartzitic sandstones marked with ripple marks and sun cracks. . . ." More recently Wagner (1949, p. 13) adds that "A majority of the quartzite bedding plane surfaces show ripple marks while many of the shale beds show mud cracks. Several of the impure quartzite beds show mud cracks superimposed on ripple marks." However, he discusses neither the specific character nor the relationship of these structures.

The Striped Peak material under study is mostly light to medium gray to pale pink (weathering reddish-brown to

pale greenish-gray), fine-grained, slightly argillaceous and silty, cross-bedded, ripple-marked, and mud-cracked quartzite. The ripple marks are approximately symmetrical, appear to be of the oscillation type, and average about 2.7 cm in width (fig. 1). The ripple mark troughs are differentially coated with a layer of ferruginous argillite. This layer has its maximum thickness in the central portion of the trough, and it thins toward the marginal crests, as in the occurrences described by Cox and Dake (1916, p. 25) and Shrock (1948, pp. 122–123). Thus in a section taken normal to the trough axis the argillaceous layer is lenticular.

The sinuous traces, which may occur either as low ridges or slight depressions on either original or cast surfaces, represent exposures of quartzitic material within and immediately adjacent to the argillaceous trough fillings. The result is a quartzite "cord" similar in composition to the overlying and underlying beds from which it generally shows partial separation on the lateral margins by an extremely thin, frequently discontinuous layer of the argillaceous material. In cross-section the "cord" is typically subtriangular (apex at bottom) in which the lateral angles lie within or at the top of the argillaceous layer (fig. 5).

On the bedding surface, the traces are irregularly to almost truly sinuous. The X coordinate axes of the curves are also the axes of the ripple mark troughs. Rarely they do occur for short distances as nearly straight lines coinciding with the trough axes. The markings vary in width from about 1 mm to 3.5 mm, averaging about 2 mm.

BIG BELT OCCURRENCE

Following the discovery of the Striped Peak material, our attention was invited to a specimen collected by Mr. Don R. Williamson[1] from near the south end of the Big Belt Mountians in southwestern Montana. This specimen is also a ripple-marked Beltian quartzite occurring immediately north of the Cleo Mine between Creyson and Dry Creeks (T. 6 N., R. 4 E.).

Except for one feature, the general characteristics of this Big Belt specimen are so nearly identical with those of the above-described Striped Peak material from Idaho, that detailed description is unnecessary for the present purpose. Immediately above the approximate center of this specimen (fig. 3) a sinuous trace is abruptly truncated and offset along a short, curved fracture, the terminals of which lie beyond the intersections with the offset trace, and which has no effect on other structures present in the rock. Moreover, this fracture, which is itself slightly offset on a crack of still smaller magnitude, appears identical in nature to the sinuous traces, except for its transverse position and smaller dimensions.

A SECOND MONTANA OCCURRENCE

Several years ago a person of unrecalled identity gave to Dr. Howard A. Coombs[2] a specimen of ripple-marked and mud-cracked quartzite which was represented as having been collected from the Beltian rocks of Montana. Although the exact locality is unknown, this specimen is in one respect the most significant of the entire group under study, for it shows the sinuous traces passing into typical mud cracks of polygonal pattern (fig. 2).

The rock is a light gray to pale pink, medium-grained quartzite. The ripple marks on this slab are broad (about 5 cm), slightly asymmetrical, and are somewhat more strongly developed at one end of the specimen than the other.

In the area of strongly-defined ripple marks the sinuous markings are also well-defined, although they are intersected and transected by a few transverse fractures. As the area of poorly defined

[1] Geologist, American Smelting and Refining Company. Wallace, Idaho.

[2] Department of Geology, University of Washington, Seattle.

FIG. 1.—Ripple mark cast of Beltian quartzite from the Striped Peak formation, Coeur d' Alene Mountains, Idaho, showing sinuous mud cracks in ripple mark troughs.

ripples is approached, the sinuous traces merge with others to form a polygonal pattern in which the sinuous traces are still apparent. Finally, in that portion

of the specimen on which the ripple marks are poorly developed, the typical polygonal mud crack pattern shows no indication of the sinuous curves. Except in the matter of areal pattern, it is not possible to make a distinction between the polygonal mud crack fillings and those which make the sinuous traces.

The sinuous markings are unusually broad in this specimen, averaging about 3 mm, and reaching a maximum of 4.5 mm.

MICHIGAN OCCURRENCE

The present authors have not examined specimens from the Ajibik quartzite described by Faul (1948, 1949, and 1950). Nevertheless, the similarity in occurrence, structure, and pattern is a strong indication that the sinuous markings on the Michigan slabs are of the same origin as those from Idaho and Montana.

Faul's (1950) Michigan material was collected from the northwest slope of a steep hogback of the Huronian Ajibik quartzite in the SE $\frac{1}{4}$ sec. 30, T. 48 N., R. 27 W.

The Ajibik quartzite is described as moderately pure, thin-bedded to massive, light-colored (grey through white to pink), and commonly with ripple-marks and cross-bedding. The quartzite is separated, along bedding planes, by a thin layer of ferruginous material.

Faul (1950, p. 103) describes the sinuous markings which he identifies as "burrows," as follows:

"Two trails measured approximately two feet long and five others ranged from 2 to 8 inches in length. The traces were 3 to 5 mm wide, slightly raised, non-annulate, very gently to broadly sinuous, and in no case were they observed to branch distinctly. Thin sections . . . show that the marks are not simple trails such as are produded by recent millipedes, gastropods or by floating objects dragging on the bottom. Instead they appear to be uniform sinuous ropes of sand, closely following the uneven bedding surfaces, but separated from them by a thin film of ferruginous material much the same as the coating of the bedding planes themselves.

"I am ignorant of the type of organism which made the burrows. It would appear that the animal was digging on the surface or at slight depth, following the old bedding planes."

COMPARISON OF AJIBIK AND BELT MATERIAL

The Ajibik quartzite specimens as described by Faul (1948, 1949, and 1950) have the following characteristics in common with the material from Idaho and Montana:

1. All occurrences are in late Cryptozoic sediments.
2. The traces are confined to similar ripple-marked quartzites.
3. The quartzite strata are separated by thin argillaceous layers.
4. Most of the markings may be described as sinuous.
5. The fillings, of which the traces are longitudinal sections, consist of non-annulate "cords" or "ropes" of quartzite.
6. Structural relationships, as observed in transverse thin section appear identical. (See Faul, 1949, fig. 2; Faul, 1950, p. 104, fig. 2; this paper, fig. 5).
7. In all cases the features under consideration are confined to bedding surface zones.
8. Linear dimensions are comparable. Faul (1949 and 1950) mentions traces up to 2 feet; one of the specimens from the Striped Peak formation shows an axial length of 23.5 inches with no indication of termination at either end.
9. Trace widths are comparable. The described Michigan traces range in width from 3 to 5 mm; those from Idaho and Montana range from 1 to 4.5 mm, averaging about 3 mm.

Some difference between the Michigan specimens and those from the Belt is possible, however. Faul (1950, p. 103) states that "in no case were [the traces] observed to branch distinctly." Several of the Idaho and Montana markings show branching with variable distinctness. Another possible distinction may occur in the relationship of the trace and

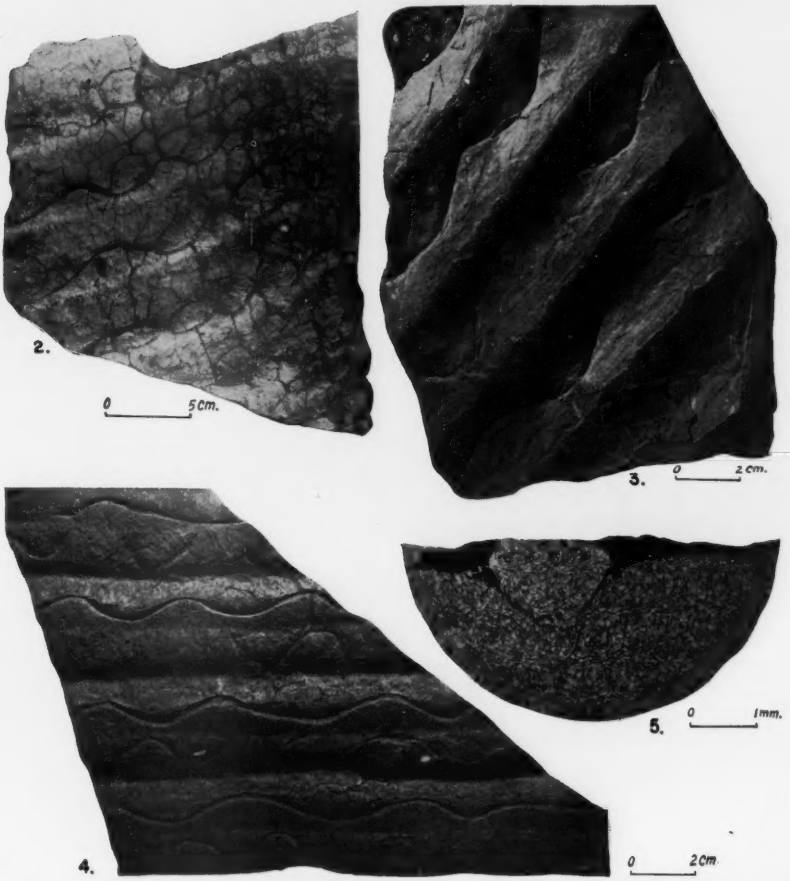


FIG. 2.—Ripple-marked Beltian quartzite from Montana, showing the merging of sinuous and polygonal mud cracks.
FIG. 3.—Ripple-marked Beltian quartzite from the Big Belt Mountains, Montana, showing sinuous mud crack offset on small transverse mud crack.
FIG. 4.—Striped Peak quartzite specimen, showing sinuous mud cracks in casts of both troughs of compound ripple marks.
FIG. 5.—Photomicrograph of transverse section of mud crack filling in Striped Peak quartzite. Dark area represents the argillaceous layer.

ripple mark axes. Faul (1948) states that "the trails cross ripple marks in gently curving wavy lines. . . . "

Most of the above-cited characteristics, however, indicate that the sinuous markings described from the Ajibik quartzite of Michigan and those from the Belt quartzites of the Coeur d'Alene and Big Belt Mountains are of common origin.

INTERPRETATION

On the basis of the following summation of characteristics, the origin of the sinuous traces on the Idaho and Montana specimens seems assured:

1. In all specimens without polygonal or other intersecting fractures, each ripple mark trough is occupied by a single sinuous trace. The possibility seems most remote that each trough would be occupied by one (and only one) worm or other organism. An apparent exception to this rule may be seen in the case of compound ripple marks (fig. 4), where both primary and secondary troughs may carry traces.

2. In general the sinuous markings exhibit a regularity which we can conceive only as the result of relatively uniform structural relationships. It seems probable that the curvature of organic burrows would be somewhat less regular.

3. Width of the traces is roughly proportional to the ripple mark wave lengths, which is to be expected in the case of fractures resulting from volumetric shrinkage of the argillaceous layer.

4. As previously stated, on the Big Belt specimen (fig. 3) a sinuous mark is offset along a doubly-terminated, transverse shrinkage crack that is interpreted as penecontemporaneous. Because both marks appear to be identical in structure, and because the arrangement defies explanation on an organic basis, the sinuous trace is also identified as a mud crack filling.

5. Evidence that the sinuous traces are quartzite filled shrinkage fractures is illustrated by the Beltian specimen of unknown locality (fig. 2). The gradual and complete merging of polygonal and sinuous patterns leaves no doubt as to the origin of the latter.

It is concluded therefore that the Beltian structures from Striped Peak and the Big Belt Mountains are mud cracks of a previously undescribed type, and that the evidence for the organic origin of similar structures in the Ajibik quartzite of Michigan should be reexamined.

REFERENCES

Cox, G. F. and Dake, C. L., *1916*. Geological criteria for determining the structural position of sedimentary beds: *Missouri Univ. School of Mines Bull.*, vol. 2, no. 4, pp. 1–59.

Faul, Henry, *1948*. Pre-Cambrian fossil trails from the Ajibik quartzite in Michigan: (Abstract) *Geol. Soc. America Bull.*, vol. 59, p. 1320.

———, *1949*. Fossil burrows from the pre-Cambrian Ajibik quartzite of Michigan: *Nature*, vol. 164, p. 32.

———, *1950*. Fossil burrows from the pre-Cambrian Ajibik quartzite of Michigan: *Jour. Paleontology*, vol. 24, no. 1, pp. 102–106.

Fenton, C. L. and Fenton, M. A., *1937*. Belt series of the North: *Geol. Soc. America Bull.*, vol. 48, pp. 1873–1970.

Kindle, E. M., *1926*. Contrasted types of mud cracks: *Royal Soc. Canada Proc. and Trans.*, vol. 20, no. 4, pp. 71–75.

Ransome, F. L. and Calkins, F. C., *1908*. The geology and ore deposits of the Coeur 'dAlene district, Idaho: *U. S. Geol. Survey Prof. Paper* 62.

Shrock, R. R., *1940*. Rectangular mud cracks: *Wisconsin Acad. Sci. Trans.*, vol. 32, pp. 229–232.

———, *1948*. Sequence in layered rocks: *McGraw-Hill Book Co. Inc., New York*, 507 pp.

Wagner, W. R., *1949*. The geology of part of the south slope of the St. Joe Mountains, Shoshone County, Idaho: *Idaho Bur. Mines and Geol.*, paper no. 82.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 3, PP. 147–150
FIG. 1, SEPTEMBER, 1951

PLAYA SEDIMENTS OF ROSAMOND DRY LAKE, CALIFORNIA

WARREN B. HAMILTON
University of Oklahoma, Norman, Oklahoma

ABSTRACT

Samples of playa sediments from Rosamond Dry Lake, in the southwestern part of the Mojave Desert, have been analyzed mechanically. These playa sediments are chiefly clays of extremely fine grain size; in five of the six analyses, more than half of the sample was found to be finer than 1 micron in diameter.

INTRODUCTION

Rosamond Dry Lake is one of several slightly separated playas in Antelope Valley, the southwestern portion of the Mojave Desert in east-central California. The playa lies partly in Kern County, partly in Los Angeles County.

Rosamond Dry Lake is easily accessible. A paved road connects it to the town of Rosamond, 3 miles to the west on U. S. Highway 6.

A reconnaissance geologic map of the region has been made by Simpson (1934), and the alluvium of Antelope Valley has been studied by Johnson (1911) and Thompson (1929).

ACKNOWLEDGEMENTS

Thanks are due K. O. Emery of the University of Southern California for his guidance in the laboratory phase of this work and for his assistance with the manuscript.

Laboratory analyses were made in the sedimentation laboratory of the Hancock Foundation of the University of Southern California.

ANTELOPE VALLEY

Antelope Valley is a closed basin with an extent of 70 by 50 miles. The south, southwest, and west part of the rim is formed by, respectively, the San Gabriel, the Sawmill-Liebre, and the Tehachapi Mountains. From these ranges, alluvial fans slope to the playas in the north part of the valley. The northern and eastern border of the basin is formed in part by low buttes and hills but mostly by slight divides on pediments and fans. The rim elevations range from over 9,000 feet (in the San Gabriel Mountains) to the low point of 2,360 feet northeast of Rosamond Dry Lake. The surface of Rosamond Dry Lake itself ranges in elevation from 2,271 to 2,278 feet.

Well data show the Antelope Valley alluvium to consist of interbedded, interfingering, and gradational gravel, sand, silt, clay, and hardpan, with only a slight directional coarsening shown in the lower part of the valley (Johnson, 1911). The upper 500 feet of alluvium in the lower part of the valley is typically about half clay, half sand and gravel. The maximum alluvial depth is not known; one well near Lancaster penetrated shale (consolidated valley fill) at 1,300 feet and was still in alluvium at 2,000 feet (Thompson, 1929).

Antelope Valley soils are gray or buff, high in soluble minerals, low in organic material, and without sharp contrast between surface and underlying material.

Impervious rocks surround and underlie the valley. Where the surface of the sill is of porous material, impervious rocks apparently underlie it at shallow depth.

Perennial lakes have undoubtedly occupied part of Antelope Valley in the past. Most of the clay known in well sections is believed to have been deposited under standing water (Thompson, 1929). A sill-depth lake has been postulated by

Thompson (1929), and Miller (1946) has suggested that the lake, presumably Pleistocene, be called Lake Thompson. Although large lakes have undoubtedly been present, no good physiographic evidence has been recognized as yet to prove the existence of a geologically recent lake having a depth of more than perhaps 40 feet, as opposed to the depth of about 85 feet needed to reach the sill level.

ROSAMOND DRY LAKE

Rosamond Dry Lake is the westernmost of the three Antelope Valley playas, Rogers ("Muroc"), Buckhorn, and Rosamond, lying in the northern part of the valley and now only slightly separated from each other.

Rosamond playa is roughly circular with a diameter of about 6 miles. Most of the playa surface is a featureless plain, lower by several feet at its center and north side than at the south. The alluvial slopes are likewise almost featureless, but the playa and fans are separated by low dunes, lake bars, and beach sediments that form a broken ring around most of the playa.

Rosamond Dry Lake is bounded on three sides by alluvium, but on the north it reaches nearly to a low escarpment of probable fault origin at the foot of a quartz monzonite pediment rising northward toward low buttes. Tertiary volcanics and continental sediments have been downfaulted against the quartz monzonite northwest of the playa.

Water on the surface of the playa during wet seasons comes mostly from rainfall in the lower part of the valley. Mountain runoff evaporates or moves under the valley in aquifers, now heavily tapped for domestic and agricultural uses but formerly providing an artesian head over a considerable area. The average annual precipitation is about 5 inches, mostly falling in the months between December and March. Evaporation of water from open containers is on the order of 110 inches annually, an amount far in excess of that ever present on the playa during the wet season. Mean January and July temperatures are, respectively, 45° and 80° F., with extremes of about 10° and 120° F.

The playa surface remains mushy for a considerable period after standing water has disappeared, but drying produces a surface which permits high speed automobile driving. The distribution of standing water and soft areas following a rain is quite irregular.

A few circular mounds 300 feet in diameter and a foot or two high with artesian springs at their summits form interesting but minor features on the playa. They appear to be due chiefly to the holding of wind-blown sediment by moisture, but cattle manure and sediment brought up by the water have perhaps added to them.

PLAYA SEDIMENTS

The playa sediments of Rosamond Dry Lake are fine-grained clays containing silty layers and wind-transported sand.

Surface clays are a pale reddish buff when dry and darker reddish brown when wet, and the subsurface clays are light grayish buff when dry and darker, somewhat greenish, when wet.

Six samples of the Playa sediments were analyzed mechanically for grain-size distribution. The results are shown by the accompanying histograms (fig. 1). The samples were chosen to be representative rather than uniform, and several of them accordingly had bands of different grain sizes.

Three of the clay samples are from the playa surface (one near the southeast edge, one near the center, one near the northwest edge), and each represents the top one-half inch of sediment. The other three samples are from depths of 12, 36, and 48 inches in a hole near the playa center, each sample representing a stratigraphic thickness of about one-half inch.

A large proportion of each of the playa samples is extremely fine grained. The finest—the surface sample from the playa center—was found to have 77 per cent

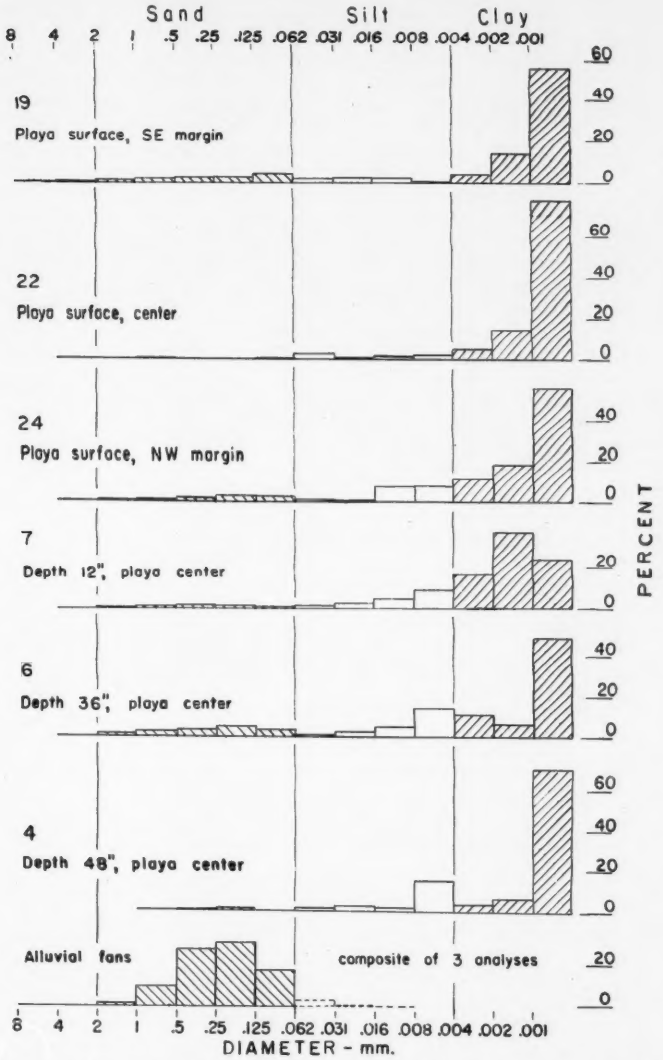


FIG. 1.—Histograms of mechanical analyses of playa sediments from Rosamond Dry Lake. The bottom plot is for alluvial fan material at the playa margin and is included for comparison. Note the extreme fineness of the sediments. The low peaks in the sand sizes represent wind-carried sediment, and the silt peaks of samples 4 and 6 are due to the presence of silty layers in the samples.

of its sediment finer than 1 micron in diameter and 40 per cent finer than one-half micron. The fraction finer than 1 micron was not further divided in the other samples. Only one of the six samples analyzed had appreciably more than 50 per cent coarser than 1 micron.

In the surface samples, sand-sized grains are much more abundant in the marginal samples than in the one from the playa center—15 per cent and 6 per cent as against 0.5 per cent. The histograms show a low peak in the sand sizes of most of the analyses; this is the expected result of the probable deposition by wind of these sizes.

A second peak appears in the silt sizes of the histograms of two of the subsurface samples and is due to the inclusion of coarser beds in the samples analyzed. Although the surface samples are quite uniform in appearance, the subsurface clays are clearly banded with gradational silty layers in the dominantly fine clays.

It is interesting to note that the grain size of these sediments is comparable to that of marine bathyal blue muds and abyssal red clays in analyses cited by Kuenen (1950).

A composite plot of three markedly similar mechanical analyses of samples from alluvial slopes at different points bordering the playa is included for comparison with the histograms of the playa clays. This alluvial fan material is almost entirely within the sand sizes, and yet only a few yards of gradational sediment separate it from the fine playa clays.

A surface clay sample from Rogers Dry Lake was analyzed by Thompson (1929) for its soluble alkali content, and this was found to be 1.21 per cent. As this surface is similar in all apparent respects to that of the nearby Rosamond playa, the value for Rosamond alkali content should be similar.

A surface sample from the southeast part of Rosamond playa and a sample from 12 inches below the center of the playa were analyzed by K. O. Emery and found to contain, respectively, 0.20 per cent and 0.19 per cent organic carbon.

The subsurface samples contain an abundant fauna of well-preserved undescribed ostracods, whereas the surface samples contain a sparser and more fragmented ostracod fauna. As Pleistocene time must be recorded in the playa section, information of value in glacial correlations is perhaps available from a study of these ostracods.

REFERENCES

JOHNSON, HARRY R., *1911*. Water resources of Antelope Valley, California: *U. S. Geol. Survey Water Supply Paper*, no. 278.

KUENEN, PH. H., *1950*. *Marine geology:* John Wiley & Sons, Inc., New York, 568 pp.

MILLER, ROBERT R., *1946*. Correlation between fish distribution and Pleistocene hydrography in eastern California and southwestern Nevada: *Jour. Geology*, vol. 54, no. 1, pp. 43–53.

SIMPSON, EDWARD C., *1934*. Geology and mineral deposits of the Elizabeth Lake quadrangle, California: *California Jour. Mines and Geology*, vol. 30, no. 4, pp. 371–514.

THOMPSON, DAVID G., *1929*. The Mohave Desert region, California: *U. S. Geol. Survey Water Supply Paper*, no. 578.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 3, PP. 151–161
FIGS. 1–6, SEPTEMBER, 1951

THE SEDIMENTS OF LAKE ELSINORE, RIVERSIDE COUNTY, CALIFORNIA

JOHN F. MANN, JR.
Elsinore, California

ABSTRACT

About one hundred samples of beach and bottom sediments of Lake Elsinore were taken. Using the results of mechanical analyses and heavy mineral studies of the beach sediments, the shoreline has been divided into three zones. From histograms of grain-size frequency of all the samples, six distinct types of sediments were recognized. Transverse and longitudinal profiles of bottom samples were constructed showing grain-size frequency, median diameter, depth, and distance from shore, and the interrelationships of these factors are discussed. Heavy mineral suites and relative frequencies of the species are given in a histogram.

INTRODUCTION

Lake Elsinore is in the extreme western part of Riverside County, California, about 75 miles southeast of Los Angeles. This lake was selected for study because it combines a rather unique association of environmental characteristics: (1) warm, semi-arid climate (water temperatures usually remain above 39° F. and prevent spring and fall overturn); (2) highly variable salinity; (3) location in a deep graben; (4) small drainage basin with well-differentiated distributive provenances.

GENERAL GEOLOGY

Lake Elsinore lies in a prominent graben in the Elsinore fault zone, within the Peninsular Ranges physiographic province of Reed (1933). As the lake basin is a direct result of faulting, the lake has straight sides and is elongate in a northwest direction, conforming with the major structural trends of southern California (fig. 1).

The very prominent Willard fault scarp occurs southwest of Lake Elsinore (fig. 1). Here the slightly dissected front of the Elsinore Mountains rises morethan 2000 feet above the lake. Between the mountains and the lake is an alluvial apron about one-half mile wide.

Northwest of the lake the mountain face trends northeast following a major cross-fault. The lake and this scarp are separated by a flat area about a mile and a half wide.

Another broad, flat area occurs east and southeast of the lake. This area is featureless except for several masses of alluvium which were upfaulted along the Wildomar fault (Engel, 1949). Southeast of Rome Hill (fig. 1), the down faulted block between the subparallel Willard and Wildomar faults is called the Murrieta graben.

The uplifted block northeast of the lake, usually called the Perris block, presents a scarp much less impressive than the front of the Elsinore Mountains. Nevertheless, earthquake epicenters (Willis and Wood, 1922) indicate that the Glen Ivy fault is more active than the Willard fault. The Glen Ivy fault (fig. 1) occurs very close to the northeast shoreline of the lake, and near the north corner of the lake this scarp is very steep. Bedrock crops out along the northeast beach at scattered points between samples 39 and 44 (fig. 2). Southeast of the town of Elsinore the Glen Ivy fault is covered by the delta of the San Jacinto River.

DRAINAGE AREA

General Description

Before the construction of Railroad Canyon Dam (fig. 1) in 1927, the drainage area of Lake Elsinore included about

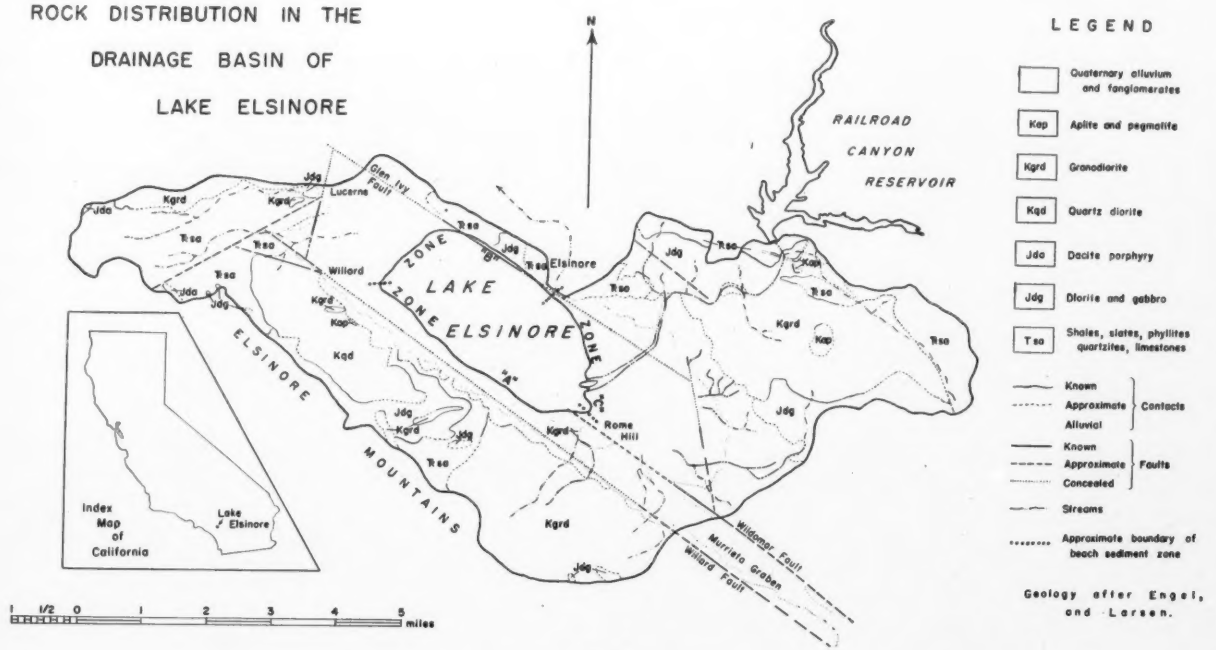

ROCK DISTRIBUTION IN THE
DRAINAGE BASIN OF
LAKE ELSINORE
N
RAILROAD
CANYON
RESERVOIR
Glen Ivy Fault
Lucerne
Willard
Elsinore
LAKE ELSINORE ZONE
ELSINORE MOUNTAINS
Rome Hill
Wildomar Fault
Murrieta Graben
Willard Fault
Index Map of California
Lake Elsinore
1 1/2 0 1 2 3 4 5 miles
LEGEND
Quaternary alluvium and fanglomerates
Kap Aplite and pegmatite
Kgrd Granodiorite
Kqd Quartz diorite
Jda Dacite porphyry
Jdg Diorite and gabbro
Tsa Shales, slates, phyllites quartzites, limestones
Known
Approximate
Alluvial
Contacts
Known
Approximate
Concealed
Faults
Streams
Approximate boundary of beach sediment zone
Geology after Engel, and Larsen.

FIG. 1

770 square miles. Except for small diversions, the run-off flowed freely into Lake Elsinore. The present drainage area (fig. 1) is only about 6 per cent of the former area. In this paper, all references to the drainage basin of Lake Elsinore indicate the present, smaller area.

The capacity of Railroad Canyon Reservoir is 12,000 acre-feet, much less than the capacity of the lake, which is 125,000 acre-feet (A. A. Young, personal communication, 1947). Despite the small volume of the reservoir, a very heavy run-off is necessary to fill it and cause overflow. During dry seasons the reservoir company has agreed to release water into the lake to maintain a specified level.

The overflow of the lake (fig. 1) is at an elevation 1260 feet above sea level. The excess water flows northeast through the town of Elsinore, then northwest up the Temescal graben to join the Santa Ana River. Because of complex geologic structure, the overflow channel near the northeast shore of the lake is almost parallel to the shoreline and less than a mile away.

Lake Elsinore appears to be existing under very precarious conditions, although the eventual means of destruction of the basin can not be stated with certainty. The shallow depth of the basin (about 40 feet) suggests that filling with sediment might be accomplished in a very short time. However, the trapping of sediment in Railroad Canyon Reservoir has somewhat increased the longevity of the lake in this respect. Destruction of the lake basin by rim erosion may occur at any of three points. There is a low lip near Lucerne (fig. 1) through which streams, formerly draining into the lake, now flow into the overflow system. The overflow, too, is subject to erosion. However, both of these channels involve flow from the graben to an active, rising block, Probably the weakest spot on the rim is the low saddle southeast of Rome Hill in the Murrieta graben (fig. 1). Here the divide is less than 100 feet above the lake bottom; southeast-flowing Murrieta Creek is eroding headward rapidly and has already captured several streams from both slopes of the graben.

Rock Distribution

The drainage basin of Lake Elsinore has been mapped recently by Larsen (1948) and by Engel (1949) and the rock distribution shown in figure 1 has been taken from their maps. On the basis of rock distribution, the drainage basin may be divided into three more or less distinct areas. Southwest of the lake the drainage basin consists chiefly of intermediate plutonic rocks, The metamorphic rocks are predominantly quartzites (Engel, personal communication, 1947) and pegmatite dikes are uncommon. The metamorphic rocks west and north of the lake are metasediments, chiefly slates and quartzites, and meta-andesite. Plutonic rocks are exposed over a large part of this area. That part of the drainage basin which is tributary to the San Jacinto River contains large areas of plutonic and metamorphic rocks and, in addition, several large dikes of aplite and pegmatite.

LIMNOLOGY

Hydrography

The bottom contours (fig. 2) are based on a survey made in December, 1946. At that time the level of the lake was 1241.8 feet above sea level. Under conditions of below-normal rainfall, the level has fallen continuously, reaching 1230.4 in September, 1949, and 1226.7 in September, 1950. These lake levels are from unpublished records of the U. S. Geological Survey.

Overturn

Lake Elsinore does not freeze; in fact, temperatures are rarely low enough to produce the spring and fall overturns associated with the maximum density of water (39° F.). At the time the bottom samples were taken (December, 1946) there was a slight odor of hydrogen sulfide in the mud, indicating some stagnation. The degree of stagnation was not

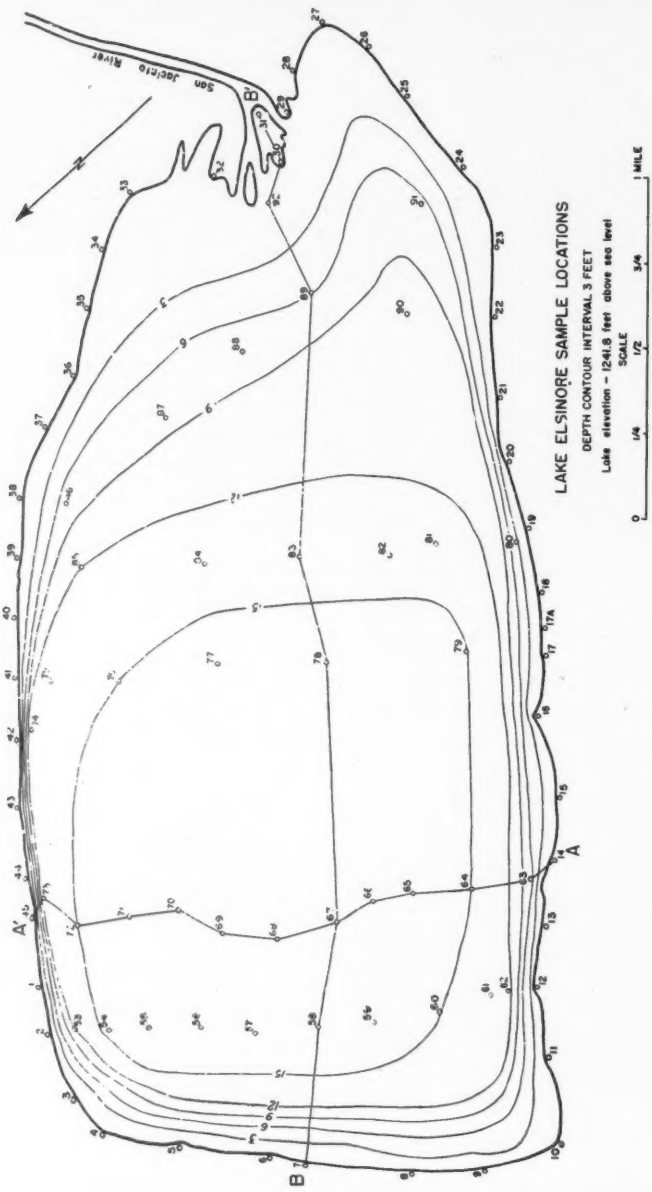

San Jacinto River
LAKE ELSINORE SAMPLE LOCATIONS
DEPTH CONTOUR INTERVAL 3 FEET
Lake elevation – 1241.8 feet above sea level
SCALE
0
1/4
1/2
3/4
1 MILE
Surveyed in December 1946
A
A'
B
B'

FIG. 2

as great as might be expected. In the lake behind Vail Dam, about 30 miles southeast of Lake Elsinore, hydrogen sulfide was abundant in the water and discolored the upstream face of the dam. The gates were first closed about November, 1948, and were not opened until late spring 1949. The water leaving the pipe at the base of the dam was yellow from precipitated sulfur, and the air in the vicinity had a strong hydrogen sulfide odor. Rocks in the stream bed for several hundred feet downstream from the dam were coated with sulfur.

Observations by McEwen (1941) at Sweetwater Lake in San Diego County prove that overturn in winter is caused by wind. Similarly, in Lake Elsinore, it is believed that periodic wind-induced overturn occurs during the winter, but that mixing is never complete and conditions on the bottom are always somewhat reducing. Lakes with this type of overturn are not included in Twenhofel's classification (Twenhofel, 1950) and the adjective *ventimictic* is proposed to describe them.

Anaerobic decomposition of organic matter is not the only source of hydrogen sulfide in the lake. Many wells in the town of Elsinore are sources of sulfurous water. On August 4, 1949, near sample 45 (fig. 2) bubbles of hydrogen sulfide were continually rising close to shore from an area approximately 100 feet by 100 feet. Bubbles were rising several weeks later from the same area. It does not seem likely that this quantity of gas could have been derived from organic decomposition; it was probably coming from the Glen Ivy fault whose trace almost coincides with the shoreline (fig. 1).

Limnobiology

Bacteriological plate tests of the bottom mud have shown the presence of sulfate-reducing bacteria. Despite the reducing environment of the mud, life in the lake in 1947 was abundant. Great numbers of carp were seined daily from half a dozen different parts of the beach; each netting removed 100 or more individuals averaging 2–3 pounds. Gastropods of the following species were found on the exposed lake bed northeast of Rome Hill; *Physella osculans* (Haldeman), *Helisoma tenue californiense* Baker, *Gyraulus vermicularis* (Gould).

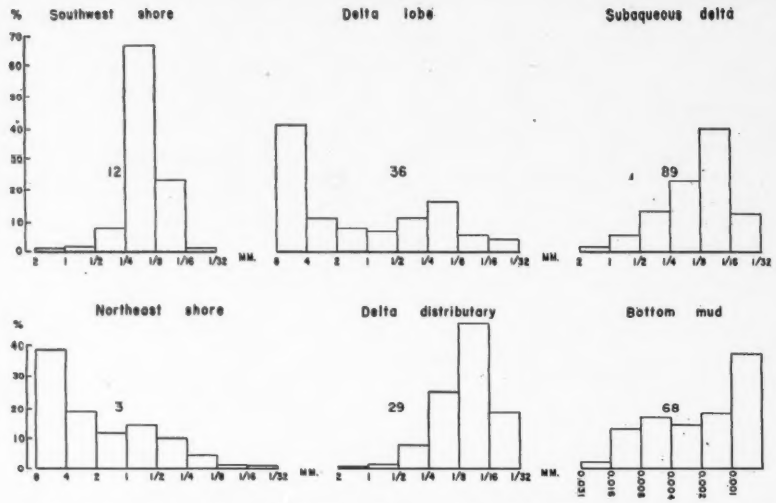
Filamentous blue-green or green algae grow abundantly on the southwest shore where they form a thin but continuous crust. Calcareous algae, which encrust bedrock outcrops and isolated rocks near shore, are especially prominent near sample 39 (fig. 2).

In the summer of 1948 a great catastrophe occurred in Lake Elsinore, In the space of a few days all the fish were killed. Hundreds of tons were removed from the beaches at considerable expense to the state. The cause for this mass killing is not known although the theory has been advanced that there was a sudden bloom of a cyanide-producing blue-green alga. It seems unlikely that either lack of oxygen or increasing salinity of the water could account for such a catastrophic killing.

The mass killing of the fish completely upset the natural faunal balance of the lake. The fish fed chiefly on bloodworms belonging to the *Chironomidae*, which can thrive in a somewhat anaerobic environment. By the summer of 1949, great swarms of these midges were found in the vicinity of the lake. On August 4, 1949, the tiny larval cases formed large accumulations on the surface of the water and along the shoreline. Along the northeast beach there was a solid deposit 4 to 5 feet wide and averaging an inch deep.

METHODS OF SAMPLING

Forty-five samples were taken along the entire shoreline of the lake at intervals averaging 1000 feet. Usually spot samples were taken at the water line, but in a few places, where the sands were streaked, composite samples were taken. Forty samples of the bottom mud were taken with a clamshell-snapper type of sampler. All of the samples shown on the lake chart (fig. 2) were located by



HISTOGRAMS OF TYPICAL ELSINORE SEDIMENTS

FIG. 3

means of a sextant. For control, six prominent points near the lake were chosen and plotted accurately from available maps, or located from known points with a sextant. All positions were plotted from double-angle sights using a three-arm protractor. The outline of the lake was drawn from the positions of the shoreline samples and field sketching. Contours of the lake bottom are based on soundings recorded while sampling (fig. 2).

METHODS OF ANALYSIS

Selected shoreline samples were sieved in Stanard Tyler screens. Samples of the lake mud, which had been placed in cloth bags, became extremely hard upon drying and could not be prepared for dry sieving. After overnight digestion in 0.01 normal sodium oxalate and frequent mixing, however, the mud was dispersed. It was then wet-sieved through a 0.061 mm. screen and the silt-clay fraction was analyzed by the pipette method. The 1/16–1/8 mm sieve fractions were used for heavy mineral separations in bromoform (sp. gr. 2.89).

DESCRIPTION OF SEDIMENTS

Zone A

The shore of Lake Elsinore has been divided into three zones (fig. 1), based on grain-size distribution and heavy mineral content. Sample 12 (fig. 3) is a typical example of the well-sorted sands that are found on the southwest shore. This debris is derived from the intermediate plutonic rocks and quartzites of the Elsinore Mountains, and the grains are essentially unabraded. Some sorting is accomplished on the beach, as shown by black streaks very rich in hornblende. The skewness toward the finer sizes may result from a concentration of smaller grains of hornblende with the larger grains of quartz and feldspar.

Zone B

Sediments derived chiefly from metamorphic rocks (sample 3, fig. 3) are very coarse. A secondary mode at ½–1 mm

is caused by the presence of dioritic detritus. Rounding of the metamorphic pebbles was probably accomplished chiefly on the beach, as net transport was less than 2 miles. Alternating pebbly and sandy streaks on the northeast beach suggest that at times the waves are competent to shift pebbles a short distance. Wave activity is more positively shown by the removal of fine material through winnowing.

Zone C

The deltaic sediments are of two different types. The San Jacinto River flows into the lake only during heavy rains, at which times Railroad Canyon Reservoir becomes filled and overflows. Because torrential flow of this sort has a high competency, the small lobes of the delta are higher and contain coarser material than the channels of the distributaries. The lobal sediments resemble the metamorphic beach material, but in the former the finer components have not been winnowed out so efficiently. As can be seen from a histogram of a lobal sample (36, fig. 3), the primary mode occurs in the same grade size as in sample 3, but the secondary mode occurs in a finer grade size. In the distributaries, where deposition occurred at times of lower flow, the sorting is considerably better (sample 29, fig. 3).

Bottom Deposits

The sediments of the bottom of the lake are of two main types. In the shallow southern portion of the lake, on the delta, is a compact micaceous sand. The histogram of sample 89 (fig. 3) is typical of this sand. The deltaic sands grade into the finer sediments of the flat botttom (fig. 2), which are uniformly a greenish-black mud, having, when sampled, the consistency of corn-starch pudding.

A histogram of the mud (sample 68, fig. 3) shows that most of the particles are of clay size, and that sorting is poor. Poor sorting is to be expected in deposits of this type, because they consist of all the material supplied to the depositing currents. At any particular moment, waves and currents are capable of moving grains below a certain hydraulic radius to deeper water. Such a load is indiscriminately dumped in its final resting place, the deeper parts of the lake. Sorting, then, is necessarily the same as the sorting of the material supplied, as no further transportation of the particles is possible in the present cycle of sedimentation.

Profiles of Bottom Deposits

Mechanical analyses of bottom samples on a transverse profile (A–A′, fig. 2) and a longitudinal profile (B–B′, fig. 2) are plotted in figures 4 and 5 respectively. Figure 4 shows that sandy sediments are restricted to narrow belts near shore. Waves and currents are obviously not competent to remove sand-size particles to deeper water. The small amount (0.5 per cent) of sand in the bottom mud consists chiefly of ostracode carapaces and fish scales, but with some detrital mineral grains. Small patches of floating sand in small lagoons near shore suggest that the detrital grains may be floated out to deeper water. But at times, the wind may have a velocity sufficient to blow sand (especially flakes of mica) over the lake.

In profile A–A′ the relationship between median diameter and depth is very marked. Equally striking is the poor relationship between median diameter and distance from shore. The difference in slope between the northeast and southwest sides of the lake basin is shown here more clearly than by the contours of the bottom (fig. 2). The southwest slope is essentially the slope of an alluvial fan; the northeast slope is also the slope of an alluvial fan, but one which has been steepened by uplift. The more gradual decrease of median diameter in the bottom mud near the northeast shoreline, as compared with the sharper decrease near the southwest shoreline, seems anomalous because the northeast slope is steeper. This anomaly seems explainable on the basis of supply. It

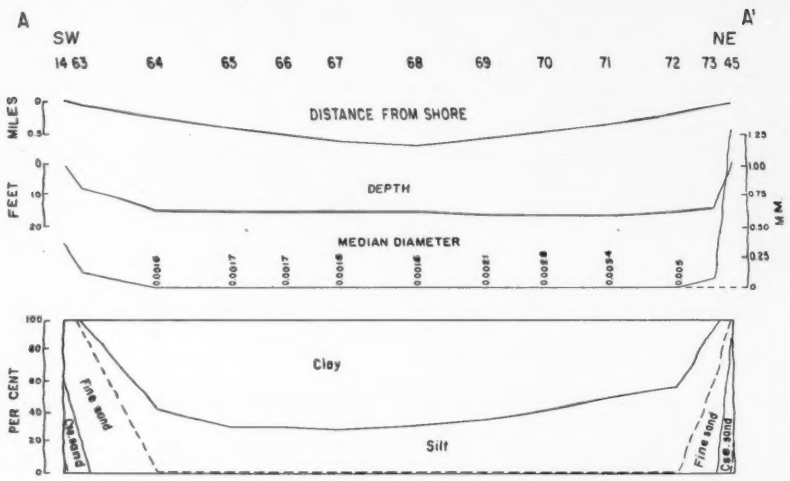


FIG. 4

is suggested that the destruction of metasediments produces more silt-size particles than the destruction of the plutonic rocks. The sharper climb of the median diameter near the northeast shoreline suggests that winnowing here is more effective, although the increase is due in part to the sizes of the materials supplied.

On the left side of profile B–B′ conditions are similar to those of profile A–A′; however, the right side, on the delta, is much different. Samples 30 and 31 were taken on the subaerial part of the delta and are not considered lake bottom deposits; they show the poor sorting and large grain sizes of torrential deposits. On the subaqueous part of the delta (fig. 2) the median diameter appears to be related to *both* depth and distance from shore. The inflowing river waters carry sandy material well out into the lake and deposit there well-sorted, generally micaceous sediments. The predominance of plutonic rocks in the area tributary to the San Jacinto River, as in the Elsinore Mountains, is indicated by the low percentages of silt-size particles.

The use of these profiles to calculate the velocities of currents in the lake was demonstrated in an earlier paper (Mann, 1949).

Organic Matter

Incidental to other microscopic studies, various types of organic matter were identified. Ostracode carapaces were found in almost all of the bottom samples, and platy fragments of them, under the petrographic microscope, bore a striking resemblance to muscovite. Fish scales and tiny fin rays, probably mostly from carp, were also abundant. Filamentous algae were noted in many samples. Organic matter content, determined by the method described by Allison (1935), was 0.9 per cent in sample 88 and 4.4 per cent in sample 72.

HEAVY MINERAL ZONES

Heavy mineral studies of samples along the shoreline of the lake show that these minerals reflect strongly the rocks of the backing terranes. Transportation of the detrital grains has not been extensive, and the various suites of minerals are consequently found only very close to their source rocks.

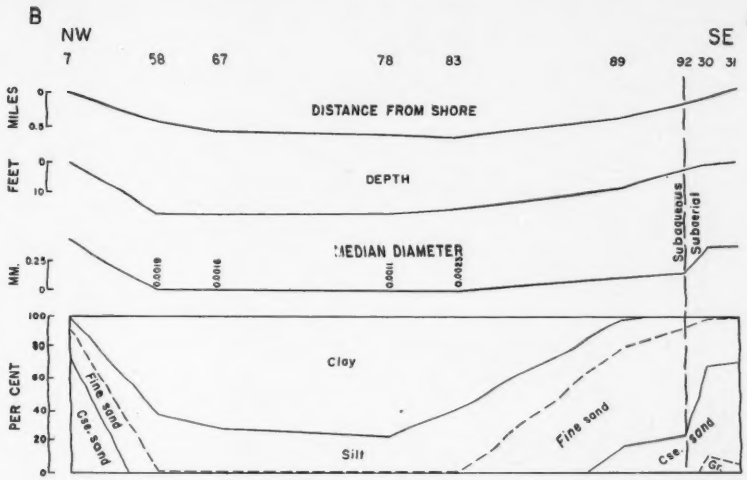


FIG. 5

Zone A (fig. 2) contains heavy minerals derived almost exclusively from the intermediate plutonic rocks; hornblende, biotite, hypersthene, chlorite, epidote, diopside, apatite, topaz, and zircon. The percentage of heavy minerals ranges from about 5 to 45 per cent, averaging 24 per cent. Hornblende occurs in almost pure layers several inches thick, which crop out on low (6 inches to 1 foot) sand cliffs at the water line. The hornblende is very angular, and would be rolled less easily than the quartz and feldspar; this may account for its concentration. Short transportation is shown by the fact that few of the grains show appreciable rounding.

Zone B (fig. 2) contains heavy minerals of the plutonic facies, plus those of the metamorphics; andalusite, kyanite, and garnet. The percentage of heavy minerals ranges from about 5 to 40 per cent, and averages 14 per cent. Some heavy mineral streaks can be observed in the sands of the northwest shore, but none occurs in the gravelly deposits of the northeast shore. Although some of these gravels show considerable rounding, the heavy mineral grains are not noticeably rounder than the grains of Zone A.

Zone C (fig. 2) contains the heavy minerals of Zone B and, in addition, grains of the pegmatite minerals; monazite, tourmaline, and cassiterite. The percentage of heavy minerals is also quite variable, ranging from about 5 to 25 per cent, and averaging 14 per cent. Rounding is no more conspicuous than in the heavy minerals of the other zones. In most samples biotite is abundant. Poor sorting and little reworking of the beach materials precludes the possibility of any heavy mineral concentrations.

Histograms of the heavy minerals in each of the zones are given in figure 6. In all the zones, hornblende is a flood mineral; biotite and the opaques are scarce to abundant. Those minerals constitute a very high percentage of all the samples and have little index value. The other minerals are shown in their relative abundance.

SUMMARY AND CONCLUSIONS

Lake Elsinore, which lies in a graben in the Peninsular Ranges, has a roughly

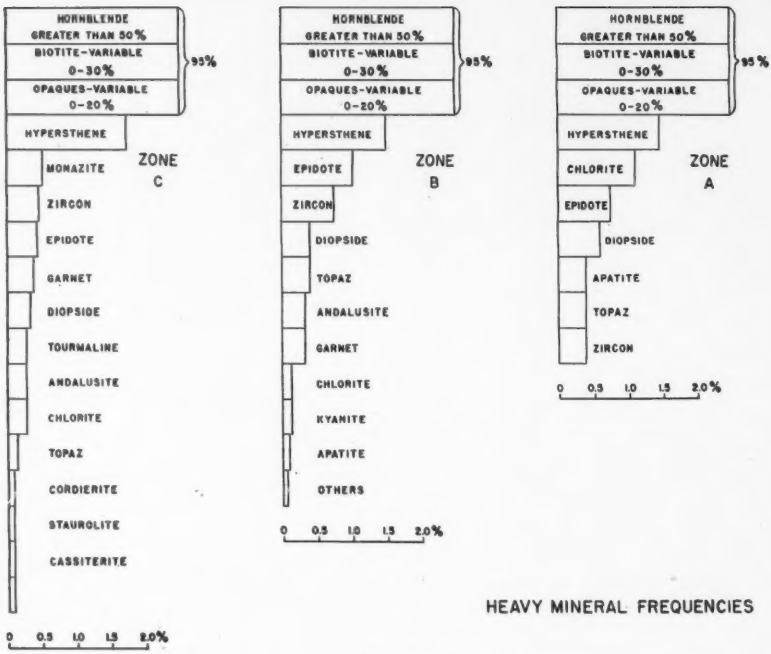


FIG. 6

rectangular shape and a very flat bottom. The present small drainage area contains outcrops of three distinctive rock groups: (a) intermediate plutonic rocks; (b) metamorphic rocks; (c) pegmatites.

Overturn, which is apparently never complete, occurs in winter due to the action of strong winds. The presence of sulfate-reducing bacteria suggests that the source of the hydrogen sulfide in the bottom mud is due partly to bacterial action; however, some hydrogen sulfide probably is derived from magmatic fluids migrating along faults. Despite somewhat stagnant bottom conditions, life in the lake in 1947 was abundant. Since 1947 great changes in the fauna have accompanied the constantly shrinking volume of water.

Waves and currents are not strong, as shown by the fact that the sandy sediments, except on the delta, are restricted to narrow belts near shore. The few sand-size detrital grains in the bottom mud were carried out to the middle of the lake as floating patches or blown there by the wind. The relationship between median diameter and depth is shown near all four shores, but on the subaqueous part of the delta the median diameter also appears to be related to the distance from shore.

Grain-size distribution and heavy minerals of the beach sediments can be closely correlated with the rocks of the backing terranes. These relationships have been used to divide the lake shore into three zones. The restricted occurrence of the heavy minerals in the beach sediments, close to their source rocks,

indicates that transportation of the detrital grains along the shore has not been important.

ACKNOWLEDGMENTS

The writer is indebted to Dr. Rene Engel, who has recently mapped the Lake Elsinore quadrangle (1949), for the loan of thin-sections and for supplying petrologic data on the rocks near the lake. Dr. S. C. Rittenberg, of the Department of Bacteriology, University of Southern California, demonstrated the presence of sulfate-reducing bacteria in the bottom mud. Wendell O. Gregg, M. D., of Los Angeles identified the gastropods, and Dr. R. L. Metcalf, of the Citrus Experiment Station, Riverside, supplied information on the *Chironomidae*. Throughout this investigation the writer has received many helpful suggestions from Drs. K. O. Emery, Thomas Clements, and D. A. McNaughton, all of the Department of Geology, University of Southern California. The bottom sampler and other equipment were used through the courtesy of the Sedimentation Laboratory, Allan Hancock Foundation, University of Southern California. The sextant was lent by Dr. F. P. Shepard, Scripps Institution of Oceanography.

REFERENCES

ALLISON, L. E., *1935*. Organic soil carbon by reduction of chromic acid: *Soil Svience*, vol. 40, no. 4, pp. 311–320.

ENGEL RENE, *1949*. Geology and economic resources of the Lake Elsinore quadrangle: *California Div. Mines Bull.* no. 146, in preparation. Geologic map printed in advance, 1949.

LARSEN, E. S., *1948*. Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, southern California: *Geol. Soc. America Memoir* 29, 182 pp.

MANN, J. F., *1949*. Bottom sample profiles of Lake Elsinore, California: *Compass*, vol. 26, no. 4, pp. 320–327.

MCEWEN, G. F., *1941*. Observations on temperature, hydrogen-ion concentration, and periods of stagnation and overturning in lakes and reservoirs of San Diego County, California: *Bull. Scripps Inst. Ocean.*, vol. 4, no. 9, pp. 219–260.

REED, R. D., *1933, Geology of California:* Am. Assoc. Petroleum Geologists, Tulsa, 355 pp.

TWENHOFEL, W. H., *1950. Principles of Sedimentation*, 2d Ed., McGraw-Hill Book Co., Inc., New York, 673 pp.

WELCH, P. S., *1935. Limnology:* McGraw-Hill Book Co., Inc., New York.

WILLIS, BAILEY, and WOOD, H. O., *1922*. Fault map of California: *Seismol. Soc. America*.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 3, PP. 162–172
PLATES 1–2, FIGS. 1–6, SEPTEMBER, 1951

GRAIN ORIENTATION IN SANDS AND SANDSTONES

W. SCHWARZACHER
The Sedgwick Museum, Cambridge, England

ABSTRACT

A method for measuring three-dimensional shape orientation of sand grains is described. Sediments were deposited under different experimental conditions. Fabric studies of these sediments reveal two types of orientation, one caused by high and one by low rates of deposition. In some cases it may prove possible to discriminate between wind and water deposition, but no satisfactory way was found of describing such slightly differing fabric patterns in numerical terms.

INTRODUCTION

Fabric studies of clastic sediments are interesting for two main reasons. First, depositional fabrics afford good opportunities for the study of grain-shape orientation processes and certain questions of more general interest. Secondly, the sedimentary petrologist may learn something about depositional conditions and thereby gain a further insight into the history of a sediment. This paper is mainly concerned with the latter question.

Several studies dealing with fabrics of sediments have been published. Sander (1930, pp. 279–281) examined oscillation ripple-marks in sandstones and found a preferred orientation of the optic axes of elongated quartz grains parallel to the axes of the ripples. Later, Ingerson (1940) obtained similar results. A great deal of work also has been done on the orientation of pebbles in the fluviatile and glacial environments.

It is comparatively easy to prepare dimensional orientation diagrams where particles can be sampled singly. The sampling technique was specially developed by Wadell (1936) and Krumbein (1939), but this is impracticable with particles as small as sand grains. Determination of the three-dimensional orientation of a grain from a single section is obviously impossible. The construction of a statistical orientation from three perpendicular sections (considering the grains as triaxial ellipsoids) is too complicated unless a plane of fabric symmetry is known. Dapples (1945) obtained accurate two-dimensional orientation diagrams from a rough surface by measuring the actual projections of long grain axes in a given plane. Rowland (1946) improved the study of sandstone fabrics by giving a quantitative correlation between dimensional and optic directions. He was thus able to construct statistical dimensional orientation diagrams from the optic axis diagrams.

Hitherto a method of measuring the dimensional directions of single grains has been lacking. The following technique has been used successfully in a number of cases where detailed fabric studies of sandstones were wanted.

METHOD

Thin plates of the specimen (sandstone) were cut in known directions and their surfaces roughened so that it was possible to view the grains in their original positions under a binocular microscope. Success depends entirely on one's being able to make such roughened surfaces.

For weakly cemented sandstones and loose sands, peels were used. A suitable plastic (e.g., "Perspex") was dissolved in chloroform, and the rather stiff paste was poured over that part of the surface to be examined. The hardened film was then pulled off and mounted on a slide. If

the paste was not too stiff, several layers of grains were easily obtained on the film. To check that the original positions of the grains were not affected by this process, different peels of the same specimen were compared.

Loose sands were also hardened with potassium silicate (waterglass) and some with plaster of Paris. The last method proved both simple and rapid. A thin cream of plaster of Paris and water was merely poured over the surface to be examined, penetrating several layers of grains and forming a fairly well cemented specimen which was easily examined.

Actual measurement of grain-orientation was done with a simplified two-axis universal stage specially constructed for the purpose. The dimensions and constructional details of this instrument may be seen in figure 1. Two discs were mounted concentrically sharing a common axis, A_1. Strike angles could thus be read on the periphery. The whole stage was rotatable about a horizontal E-W axis, A_2. Dip angles could then be read from a protractor connected with A_2. If the stage was centered, A_1 and A_2 intersected at a point on the surface of the preparation and, of course, in the optical axis of the binocular. To vary the distance between stage and slide, the latter was mounted on a broadheaded screw in a small block of metal (*B* in fig. 1). Parallel movement of the slide was facilitated by incorporation of a mechanical stage.

It is absolutely essential that *every grain*, and *only those grains*, which pass the intersection of the crosswires, should be measured. This rule must be strictly kept, because a rough surface encourages, much more than is usual in normal universal stage work, an unconscious selection of grains.

The procedure of measurement is simple. The longest axis of a grain is brought to the N-S by means of A_1 and to the horizontal position by means of A_2. If the dip of the grain-axis is too steep, the longest axis is brought to the vertical position. As usual, the angles (A_1A_2) are plotted on an equal-area stereographic net. The stereoscopic view obtained with a binocular microscope allows sufficiently accurate estimation of both horizontal and vertical. Errors of measurement arise not so much from failing to bring the grain to true horizontal or true vertical, as from misplacing the longest axis of the grain. Repeated measurement of one grain shows an average error of approximately 5°, and this never exceeds 10°.

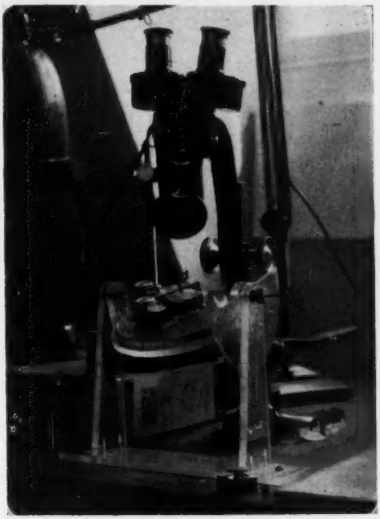


FIG. 1.—The two axes stage.

The choice of a representative direction in a grain is a most important matter and has been discussed by Dapples (1945). In the present work the "least projection elongation" was plotted as the longest direction (*ld*).

All determinations of *ld* were visually estimated. This saved a great deal of time and proved accurate enough provided several hundred grains were measured.

As one direction alone cannot fix a grain's position, diagrams of the "maximum projection area" (Krumbein, 1939, p. 677) were prepared where necessary.

Several attempts also were made to plot "end positions" (Dapples, 1945, p. 251), but this was not followed up because the results obtained were not always significant.

GRAPHICAL PRESENTATION AND INTERPRETATION

As mentioned, all data were plotted directly on a "Schmidt" equal-area net. By convention in fabric analysis, this stereographic net represents the inside of the lower half of a sphere. Therefore, all south-dipping directions appear on the southern half of a circle, north-dipping directions on the northern half, and so on. The diagrams are presented in the familiar contoured form of orthodox petrofabric diagrams. This was chosen because of its high interpretative value. Current-vectors, if represented in the diagrams, were found by considering all the features of symmetry and judging the symmetry axis visually. In this way the current-direction of a diagram was actually determined with higher accuracy than by computing a mean azimuthal direction. The latter is done by grouping strike angles of grain directions into 20° classes. The moment analysis of the resultant frequency distribution yields mean values and standard deviations (Krumbein, 1939).

Standard deviations of dip and strike distributions have been used for *approximate* descriptions of orientation patterns. However, there is still no satisfactory way of making statistical analyses of fabric diagrams.

TRANSPORTATION AND DEPOSITION OF SAND

Theoretically, it is important to distinguish as clearly as possible between the transportation and deposition of sand particles. One must bear in mind, however, that no sharp limits exist between these two processes. Transportation can be fully described only by reference to a complicated sequence of deposition, erosion, and redeposition. On the other hand, deposition is influenced in many ways by preceding transportation. Now each depositional process is inherently an orientation process. When moving, a grain has its own orientation ("translation orientation," Dapples, 1945, p. 248); when it finally reaches the bottom, it takes up the most stable position, viz. that position symmetrical to the vectors which hold and try to move it. Considering the vectors liable to be concerned in this process, we can obtain a simple classification of the possible kinds of mechanical deposition and concomitant orientation processes:

I. Sedimentation in a stagnant fluid. Gravity is the only acting force.

II. Sedimentation in flowing water. Both gravitational and current vectors are concerned.

III. Sedimentation (heaping) followed immediately by fall down a slip-face, the slope of which is controlled by the angle of repose. The latter is determined by the opposing vectors of shear-strength and gravity.

These three types of deposition correspond to Bagnold's (1941, p. 127) "sedimentation, accretion, and encroachment," terms which were used to describe depositional conditions in aeolian dunes.

FABRIC OF SHEET LAYERS

The sedimentary rock is an end product of many processes. It can be partially characterized by describing its fabric.[1] In order to investigate how far different depositional types might be represented by different fabric patterns, a number of experiments were performed in a trough. Oriented samples from artificially deposited sands were taken and measured. The measurements in diagram D.1 (plate 1) come from a finely laminated sheet, which had been deposited under conditions of "smooth phase" transport (Gilbert, 1914, p. 31).

[1] It should be noted that "fabric" is used here as a translation of "Gefuege" in the full meaning of the word. The term is in no way restricted to the description of optical axis orientation alone.

The *ld* diagram D.1 shows a good maximum in "*a*." This fabric axis is not to be confused with the longest pebble axis. There is also a pronounced girdle in "*s*" (bedding plane) and a suggestion of concentration in "*b*." The latter would represent grains with their lengths perpendicular to the current direction. The main "*a*" maximum dips upstream at about 25°–30°, giving the whole fabric a monoclinic symmetry. In every case examined, this made it possible to infer the current direction. Such an upstream imbrication is equivalent to that found in pebble beds described by Becker as early as 1893.

Again, it must be realized that the above features can be understood only in terms of equilibrium positions between the forces acting upon the grain. The stability of a grain is influenced by its position, and this position (and, therefore, the packing) is controlled by the arrangement of neighboring grains and the forces acting upon the grain (current vector field and gravity). In other words, we must expect our packing[2] to have monoclinic symmetry related to the current vector field (Sander, 1948, p. 30). Theoretically the related influences of surrounding grains and current vectors may be treated separately.

To examine the spatial relation between adjacent grains more closely the following method was used. Pairs of touching grains from D.1 were plotted in the orientation diagram with corresponding symbols, and the angles between their longest axes were determined. A typical result is given in figure 2 which shows a frequency curve of the angles between 185 pairs. In discussing this curve, it must be remembered that a constant and predominant angular relation between pairs (measured in the plane containing the two axes) does not imply a three-dimensional non-random orientation; and, conversely, that a non-random three-dimensional orientation in the whole fabric does not necessarily mean a constant and predominant two-dimensional relation between pairs. The relation between pairs to the whole fabric becomes fixed only when all grains lie in one plane (the plane in which we measure the pair-angle).

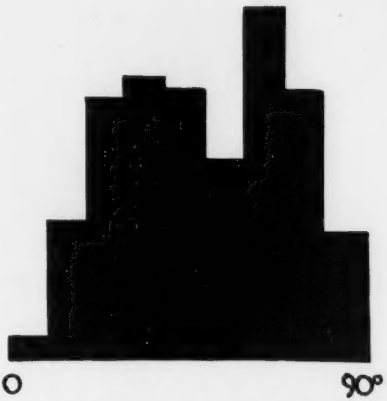


FIG. 2.—Frequency curve of contact angles between grain pairs of a topset bed.

A plot of these planes shows that they are concentrated mainly in the bedding-plane, although they are scattered over the whole projection sphere. This last fact seems to indicate that the relation between neighboring grains is much closer than that between a single grain and the general trend of orientation of the whole. In other words, one must expect some inhomogeneity in the orientation. Thus it can be seen that groups of three to six

[2] "Packing" is used in this paper in a more general sense than by Graton and Fraser (1935, p. 790) who only consider packing in a gravitational field. The word is used instead of "fabric" to stress the importance of density (a scalar fabric datum) as a function of the spatial arrangement of the particles. Little is yet known about the packing systems of non-spherical (anisotropic for shape) particles. The following questions deserve theoretical investigation at a later date: (1) What are the possible angles between grains in contact, and how are they related to grain-shape? (2) What packing systems are possible for a given symmetry? (3) What porosities and permeabilities (vectorial) would result from the above? These problems seem likely to prove amenable to universal stage technique.

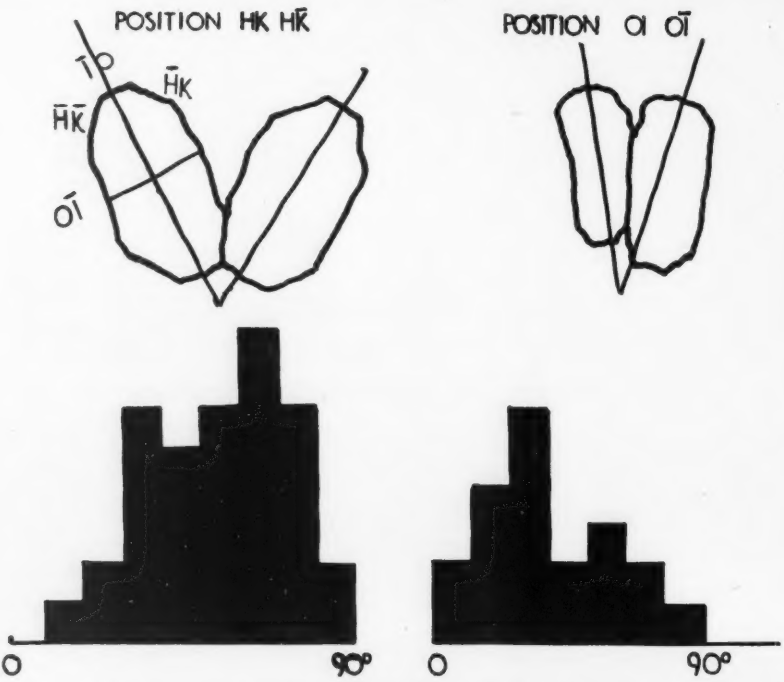


FIG. 3.—Contact angles between the two positions *hk* *hk̄* and 01 01̄.

grains ("Ueberindivideuen") tend to lie with their longest axes in the same plane, building patches of more systematic packing ("change-packing" of Graton and Fraser, 1935).

The distribution in figure 2, showing two pronounced maxima at 30°–35° and 60°–65°, suggests that there are two preferred angles between grain-pairs. Figure 3 gives two schematic grain couples with hypothetical faces 10, *hk* 01, (two-dimensional indices). From this we can determine roughly which faces act as contact faces. The two contact positions *hk* *hk̄* and 01 01̄ were found to be the most usual. Angles between *hk* *hk̄* and 01 01̄ couples are plotted separately in figure 3. The two show well that the two main packing positions are related to grain-shape.

Measurement of grain-shape showed that the faces 01 were inclined roughly at 15° to the long axis, and *hk* about 30°. Integration of this grain-to-grain relation is the reason why the maximum in D.1 is persistent on a small-circle of 30° around "*a*." To illustrate this effect, the contours for 4 per cent–2 per cent of D.1 have been rotated into the center (diagram D.1*a*).

A similar tendency to build maxima on small-circles was frequently met in deposits controlled by flow of water. Sometimes the small-circle was so incomplete that only a symmetrical double maximum appeared. Diagrams D.2 and D.2*a* exemplify such a fabric from the lower Greensands, near Leighton Buzzard (England). This relationship between grain-shape and the grain-to-grain rela-

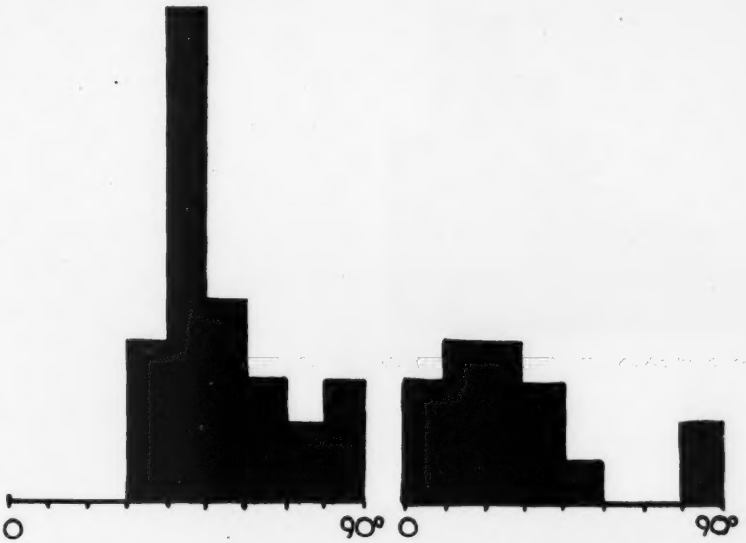


FIG. 4.—Contact angles in the two positions *hk hk* and *hk hk̄*. Sediment with low sphericity.

tion leads naturally to the problem of how the whole fabric is influenced by the shapes of the grains. A gravel (sieve fraction 1–2 mm) was fed, therefore, into flowing water and deposited in a tank as horizontal sheets. Through the entire extent of the 4 m long experimental trough much sorting according to sphericity took pace. The average sphericity was found to increase downstream, grains with lower sphericity becoming stable sooner. A sample taken 50 cm from the upstream end contained grains with relatively low sphericities (ratio of longest axis/intermediate axis 0.5–0.6; average for whole sample 0.76). The material was highly rounded and, therefore, the association of grain-contact with particular faces was rather less certain. Nevertheless, differentiation between two positions *hk* and *hk̄*, and *hk hk* was possible. Grain-pair angles for these positions are plotted in figure 4. They show that the same packing principle recurs. Although the true difference between the modes of the two positions *hk hk̄* and *hk hk* could have been disguised by misinterpretation during measurement, the nearness of the two modes (*cf.* fig. 2) and the smaller values (20° instead of 30°, and 40° instead of 60°) are typical of a case with lower sphericity. It follows, therefore, as a geometrical necessity, that with increasing sphericity (or as sphericity is mostly a function of roundness, with decreasing roundness) the maxima must become more separated. Azimuthal analyses of orientations would obviously yield standard deviations increasing with sphericity, just as was found by Krumbein (1940).

D.3 shows a plot of 100 grains (sample D.2), the three axes of each of which were measured, and from these data the ratios intermediate/longest and shortest/intermediate were determined. The symbols represent the four Zingg shape classes: disks, spheres, blades, and rods. Certain features of this diagram seem to be important. First, the more spherical grains

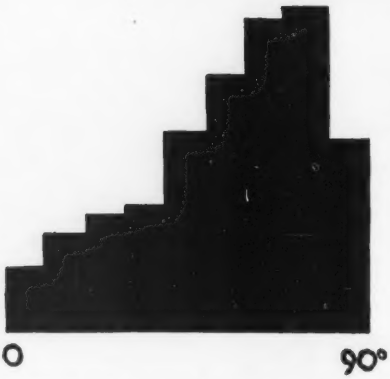


FIG. 5.—Contact angles in a foreset bed.

are, as expected, the most scattered. The information is not sufficient to demonstrate any definite regularities for the classes I, III, and IV. The rods with good azimuthal orientations seem to have the steeper dips. Sometimes there is a tendency, not seen in this particular diagram, for rods to lie perpendicular to the current direction. In any case, it is quite clear that the shape of an individual grain controls, to some extent, its final orientation.

The possibility of correlations between current velocity and perfectness of orientation was also examined, but experiments with different stream velocities yielded surprisingly uniform diagrams. A far more effective factor in controlling the orientation patterns proved to be depositional velocity, i.e., the proportion of material deposited in unit time. Different speeds of feeding sediment into a constant current gave different fabric patterns. Attempts were made, therefore, to show quantitatively that fabric change is a function of feeding velocity, but the results obtained differed too widely.

Two main sorts of orientation were distinguishable; viz., an "erosional type," and one with a high depositional ratio. Diagram D.4 exemplifies the erosional type. In this, the significantly low angle of imbrication and the relatively high contour density are to be noted.

Diagram D.5 (pl. 2) typifies the orientation in a quickly fed stream. It is seen that, compared with D.4, the imbrication is very steep (maximum about 45°) and, besides the girdle in "*s*," an incomplete girdle perpendicular to "*b*," is present. The diagram resembles somewhat the tillite fabrics described by Holmes (1941). Probably this latter girdle represents grains which had not time enough to reach full orientation before final burial. Diagrams D.4 and D.5, therefore, illustrate opposite extremes.

FORESET BEDS

The formation of foreset beds is regarded as being fundamentally different from that of sheet deposits. Foreset beds are always deposited where a step in the bottom relief induces an alteration in current conditions, causing the transportation of sand to stop abruptly. These steps may be the edge of a terrace-like layer, a ripple mark or a scoured out hollow (Shrock, 1948). As the current leaves more and more material on the lee slope, the heaped sand becomes unstable and eventually slides under gravity. During this movement it becomes oriented (see, for example, D.6 orientation in the plane of slope). Water flow has been shown to exert no influence upon the orientation processes during sliding. Orientation due to gliding was studied by heaping sand under water. Diagram D.7 is a typical example of such an orientation. A faint, but significant, orientation of *ld* in the dip direction (our "*a*") is discernible; also a girdle in the slope plane. The "*a*" maximum tends to dip up-slope. This was found in many, but not all, heaping fabrics.

Figure 5 is a plot of grain-pair angles in a foreset bed. The sand was the same as that used in the sheet layer, figure 2. The strong skewing of the curve still suggests a bimodal distribution and larger contact angles are now distinctly predominant. The modal value is in a higher class (70°–80°) than that of figure 2.

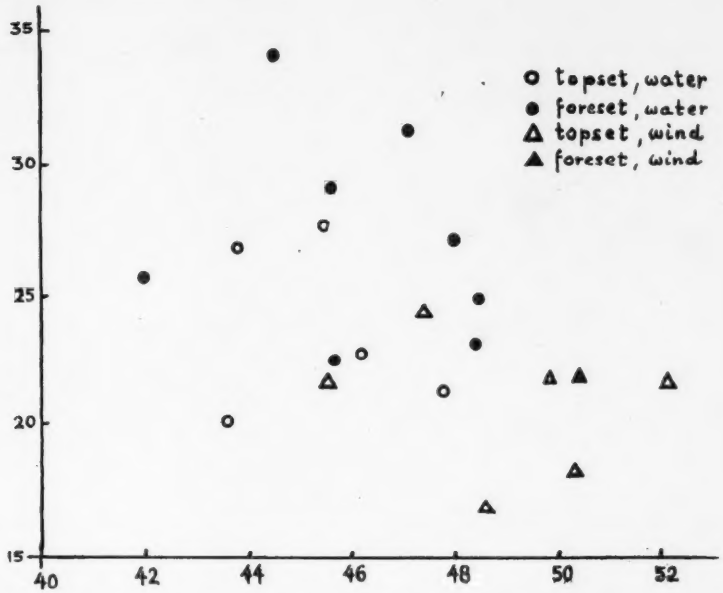


FIG. 6.—Standard deviation (σ) of dip and strike.

With the less pronounced orientation this indicates a loose (spongy) fabric of probably lower density. Bagnold's ob-observation (1941, p. 236) that lee-slopes of sand dunes behave as quicksand is interesting in this connection.

Foreset bed fabrics and sheet layer fabrics are further compared in figure 6. In this diagram standard deviations of the strike distributions are plotted against the standard deviations of the dip distributions. The diagram suggests that the standard deviations of both dip and strike are larger for foreset beds than for sheet layers, but the differences are actually very small.

WIND DEPOSITION

Specimens from the topset and foreset beds of fossil dunes (New Red Sandstone, Old Quay, north of Brodik Bay, Isle of Arran, Scotland) were measured. The diagrams D.8 and D.9 present typical results. Again, all the diagrams showed monoclinic symmetry. In all samples the imbrication dipped upwind in the topset beds and upslope in the foreset beds. The topset and foreset beds differed in one striking respect. Whereas the aeolian foreset beds proved similar to those formed in water (a not unexpected result since the heaping mechanisms are the same), the aeolian topset beds always showed well-developed maxima in "*b*." The appearance of such maxima perpendicular to the direction of transport had already been noted by Dapples (1945) in his wind experiments. Unfortunately our knowledge of this feature is not yet sufficiently reliable for use in distinguishing between aqueous and aeolian sands, because some experiments in water have also yelded "*b*" maxima. Moreover, further experimental work is necessary in order to explain fully the preferred orientation in wind-laid top-

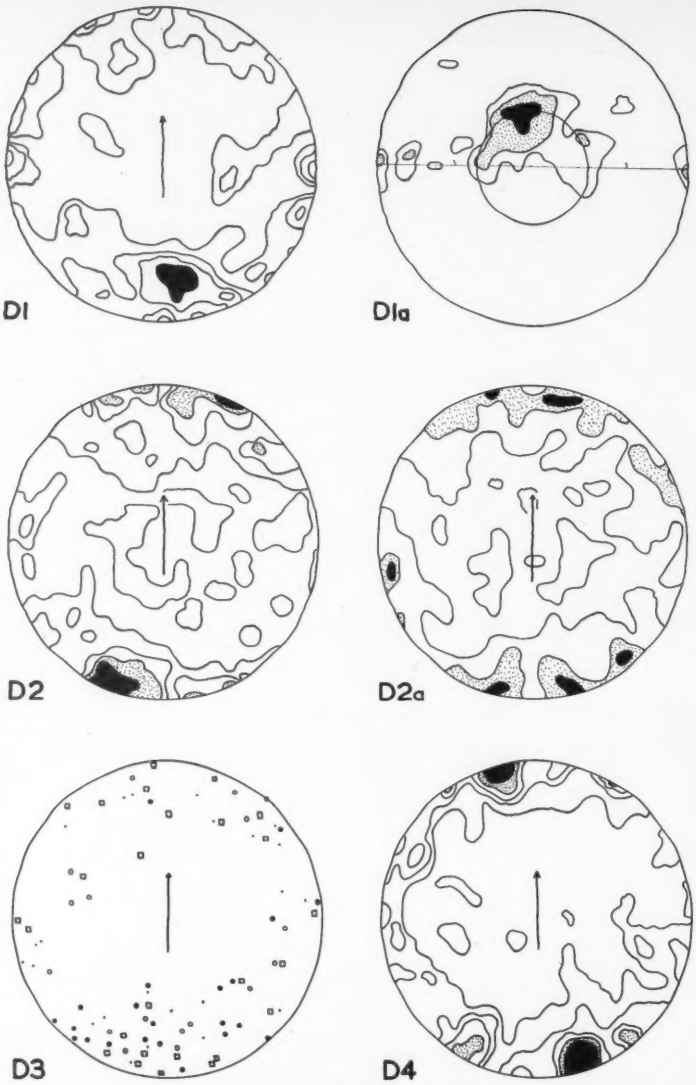


PLATE 1.—Orientation diagrams.

D.1 Petrofabric diagram of a sheet of sand experimentally deposited; 200 longest grain axes. Contours: 4, 3, 2, and 1 per cent. Arrow indicates direction of current.

D.1a As above but contours 4, 3, and 2 per cent rotated into the center. The reader is looking in the current direction.

D.2 Current fabric with double maximum; 400 *ld*. Contours: 3, 2.5, 2, 1, and 0 per cent.

D.2a From the same sample as D.2, but 400 different *ld* illustrating persistency of double maxima. Contours: 3, 2, 1, and 0 per cent.

D.3 One hundred grains classified into Zingg shape classes: empty squares = discs, dots = spheres, empty circles = blades, filled circles = rods.

D.4 Erosional fabric; 200 *ld*. Contours: 5, 4, 3, 2, and 1 per cent.

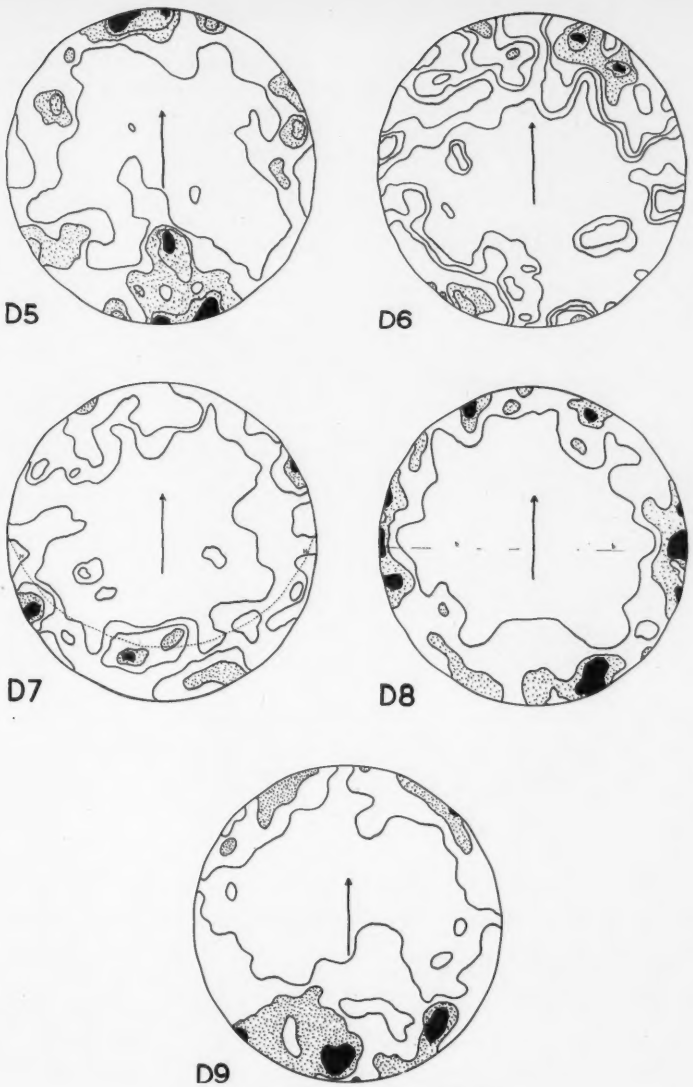


PLATE 2.—Orientation diagrams.

D.5 Petrofabric diagram of a sand with high deposition rate; 200 *ld*. Contours: 4, 3, 2, and 1 per cent.
D.6 Petrofabric diagram of a foreset bed; orientation measured in the plane of slope; 200 *ld*. Contours: 5, 4, 3, 2, 1.5, and 1 per cent.
D.7 Experimentally heaped sand under water; measured in the plane of slope; 200 *ld*. Contours: 4, 3, 2, and 1 per cent.
D.8 Fabric of a wind topset bed; 400 *ld*. Contours: 2.5, 2, and 1 per cent.
D.9 Fabric of a wind foreset bed; 400 *ld*. Contours: 3, 2, and 1 per cent.

set beds. A "*b*" maximum does not necessarily mean rolling grains. Also the much better orientation in "*s*" of wind fabrics compared with water fabrics is not yet fully understood.

Wind topset beds occupy a separate place in the standard deviation plot in figure 6. The unusually great strike deviation is, of course, due to the "*b*" submaxima.

CONCLUSIONS

The relative ease with which preferred orientation can be produced in experiments leads one to the expectation that anisotropic fabrics are far commoner than isotropic fabrics. Moreover, preliminary study of samples from different sands shows that monoclinic fabric patterns due to current action are by no means exceptional.

The classification of sediments into two groups possessing, respectively, monoclinic and spheroidal symmetry (as in igneous and metamorphic rocks, Sander, 1930) may be of value for sedimentary petrology.

On the other hand, the relative uniformity of the monoclinic fabrics studied suggests that they do not reflect current conditions as much as had been hoped.

ACKNOWLEDGMENTS

A British Council Scholarship enabled the author to work as a research student in the University of Cambridge. He wishes to thank Dr. P. Allen for supervision and much help throughout this study. He is also much indebted to Mr. R. G. C. Bathurst for reading and helping to revise the manuscript.

REFERENCES

BAGNOLD, R. A. *1941. The physics of blown sand and desert dunes:* Methuen, London, 265 pp.

BECKER, G. F., *1893.* Finite homogeneous strain, flow, and rupture of rock: *Geol. Soc. America Bull.*, vol. 4, pp. 13–90.

CHAYES, F., *1949.* From *Structural petrology of deformed rocks* by H. W. Fairbairn: Addison-Wesley Press, Inc., Cambridge, Mass., pp. 297–326.

DAPPLES, E. C., and ROMINGER, J. F., *1945.* Orientation analysis of fine-grained clastic sediments: *Jour. Geology*, vol. 53, pp. 246–261.

GILBERT, G. K., *1914.* The transportation of debris by running water: *U. S. Geol. Survey Prof. Paper* 86, 263 pp.

GRATON, L. E., and FRASER, H. J., *1935.* Systematic packing of spheres with particular relation to porosity and permeability: *Jour. Geology*, vol. 43, pp. 785–909.

HOLMES, C. D., *1941.* Till fabric: *Geol. Soc. America Bull.*, vol. 51, pp. 1299–1354.

INGERSON, E., *1940.* Fabric criteria for distinguishing pseudo-ripple marks from ripple marks: *Geol. Soc. America Bull.*, vol. 51, pp. 557–574.

KRUMBEIN, W. C., *1939.* Preferred orientation of pebbles in sedimentary deposits: *Jour. Geology*, vol. 47, pp. 673–706.

———, *1940.* Flood gravel of San Gabriel Canyon, California: *Geol. Soc. America Bull.*, vol. 51, pp. 639–676.

ROWLAND, R. A., *1946.* Grain-shape fabrics of clastic quartz: *Geol. Soc. America Bull.*, vol. 57, pp. 547–564.

SANDER, B., *1930. Gefuegekunde der Gesteine:* Springer, Vienna, 352 pp.

———, *1948. Einfuehrung in die Gefuegekunde I Teil:* Springer, Vienna, 215 pp.

SHROCK, R. R., *1948. Sequence in layered rocks:* McGraw-Hill Book Co., Inc., New York, 507 pp.

WADELL, H., *1936.* Shape and shape position of rock fragments: *Geografiska Annaler*, vol. 1936, pp. 74–92.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 3, PP. 173–177
FIG. 1, SEPTEMBER, 1951

A RAPID SUBSTITUTE FOR TEXTURAL ANALYSIS

IRVING SHERMAN
U. S. Forest Service, Arcadia, California

ABSTRACT

A rapid technique is presented which is based on the relationship between the texture and the equilibrium moisture content of an unsaturated fine-textured granular material. For a group of mineralogically similar samples, the technique makes it possible to calculate with sufficient accuracy one or more textural parameters from the results of a simple moisture content determination. This can be performed much more rapidly than the usual particle-size analysis. Limitations of the method are discussed.

INTRODUCTION

Investigators of sediments, soils, and other granular materials often need to determine the textures (particle-size distributions) of large numbers of samples within a very short time. When necessary, accuracy is sacrificed for speed; for example, the pipette technique may be discarded in favor of the hydrometer method. However, even this rapid technique may be too slow in certain circumstances.

Consideration should be given to the detail in which the textural analysis results will be used. It often happens that only one textural parameter will be used, such as the median particle diameter or perhaps the colloid content. In such cases time can be saved by using some simple test which would (a) give a result known to correlate closely with one or more textural parameters being investigated, and (b) require only a small portion of the time needed for a complete size analysis. Such a technique is here presented for the consideration of sedimentary petrologists.

ACKNOWLEDGMENTS

Correspondence with the late Dr. Kirk Bryan of Harvard University and with Dr. Luna B. Leopold of the U. S. Geological Survey prompted the preparation of this report. I wish to thank Mr. J. E. Slosson of the University of Southern California for the use of some of his data. The study of sediments in Lake Mead, cited below, was made under the direction of Mr. H. R. Gould of the Geological Survey. Mr. Slosson's study was made under the direction of Mr. H. V. Peterson and Dr. Leopold of the Geological Survey and Dr. Tom Clements and Dr. K. O. Emery of the University of Southern California. I am indebted to Dr. Leopold, Dr. Emery, and Mr. C. L. Young of the U. S. Forest Service for their critical reading of the manuscript.

PREVIOUS WORK

Investigators of soil as a medium for plant growth have had to consider soil moisture and its availability to plant roots. In their studies it was found that there is a definite correlation between soil texture and the amount of water retained in the soil for a given equilibrium condition. One example is a characteristic moisture content at which plant roots can no longer remove water (Viehmeyer and Hendrickson, 1928). In general, the moisture content increases as particle size decreases. Bodman and Mahmud (1932) used this fact in devising a method of estimating texture from the centrifuge moisture equivalent determination (Briggs and McLane, 1907) commonly made in agricultural soil laboratories. Robinson (1922) devised a technique for calculating the colloid content of a soil by measuring the soil moisture content at equilibrium with a controlled atmos-

phere. The technique presented below is adapted from that of Robinson.

PROCEDURE

1. From the entire collection of samples for which measures of texture are desired, a relatively small number are first selected for experimentation. The number so selected should be large enough to make the results statistically significant; the samples themselves should cover, as nearly as can be judged by inspection, the entire range of textures and mineral compositions represented in the entire collection. The accuracy of the technique will be improved if the collection is limited to samples which are mineralogically similar, particularly with reference to the clay minerals present. It is, therefore, usually inadvisable to include in one collection samples from widespread areas or known different geologic types.

2. Each of the experimental samples should be split into at least four representative portions. Two portions should be large enough so that a complete particle size analysis can be performed on each, and should be subjected to such analysis in sufficient detail to establish the entire particle size distribution curve. The hydrometer technique may be used here instead of the more laborious pipette method, if the hydrometer is properly calibrated (see Casagrande, 1934; and Day, 1950). The other two portions, hereinafter referred to as the "moisture samples," should be large enough so that their dry weights can be determined on whatever balance is available to an accuracy of 0.01 per cent.

3. The moisture samples should be allowed to come to equilibrium (that is, constant weight) in contact with some atmosphere. If possible this atmosphere should be kept at constant temperature and humidity. One simple method of humidity control is to place the samples in a desiccator which has sulfuric acid of known strength in its bottom. The desiccator may in turn be placed in some constant-temperature device. If equipment for humidity and temperature control are not available, the moisture samples may be allowed to stand in the open air, but the equilibrium thus reached will not always be the same and the results will be subject to some variation.

4. After reaching equilibrium, the moisture samples will be weighed and then dried at 105° C., again to constant weight. Ordinarily 24 hours suffices for this drying. The samples are then allowed to cool in an ordinary desiccator containing a drying agent and quickly weighed.

The moisture determination results will be expressed as:

$$(1) \qquad P_w = \left(\frac{W_e - W_d}{W_d} \right) 100$$

where P_w is the per cent by weight of adsorbed moisture at equilibrium, W_e is the net sample weight at equilibrium, and W_d is the net sample weight after drying.

5. A statistical correlation for the experimental samples will then be attempted between P_w and each of several textural parameters. Ordinarily, good correlations will be found between P_w and the clay contents of the samples, as the adsorbed water is considered to be held by the clay particles. The correlation will also depend on the particular clay minerals present. If the samples are reasonably uniform with respect to sorting coefficients, skewness, and organic content, good correlations may also be established between P_w and such parameters as particle median diameter. The author has found it useful to make the statistical analysis include the computation of (1) a least-squares trend line, ordinarily rectilinear, (2) the standard error of estimate about the trend line, and (3) the coefficient of correlation, for each parameter vs. P_w. The methods are taken from Arkin and Colton (1938).

6. Those correlations which show low standard errors of estimate and high coefficients of correlation may be accepted. If the parameters of texture thus correlated are sufficient for the purposes

of the study, no more size analyses need ordinarily be made. For the rest of the collection, only the equilibrium moisture determination is made. The textural parameters of those samples are computed from the empirical least-squares trend lines.

EXPERIMENTAL RESULTS

In a study of sediments deposited in Lake Mead, the author computed the correlation between P_w and the cumulative per cent of material finer than 2 microns in diameter. The determination of P_w was made as one step in a complete particle-size analysis, and for that purpose sufficient accuracy was obtained by allowing the samples to come to equilibrium with the uncontrolled air of the laboratory. The correlation with texture was computed later in connection with other work.

The laboratory room was within a massive concrete powerhouse, but both temperature and humidity were known to vary during the 9 months through which the P_w measurements were made. Temperature varied from (approximately) 20° C. to 28° C., with diurnal ranges of as much as 1.5° C. Subsequent measurements made by the Bureau of Reclamation[1] in the laboratory showed that during only a 15 day period, in which measurements were made on 12 different days, the relative humidity ranged from 33 to 48 per cent. The arithmetic mean of the 12 readings was 42.1 per cent, and the standard deviation from the mean was 4.35 per cent.

[1] Personal communication to the author from the late Mr. C. P. Christiansen.

The texture-moisture correlation was made for 273 samples, each of which was analyzed by the pipette method and by sieving. The equation for the rectilinear least-squares trend line was found to be

$$(2) \qquad y = 3.63 + 11.77(P_w)$$

in which y is the per cent by weight of material finer than 2 microns, and P_w is as previously defined. The reliability of these results may be compared with those of a later study made under slightly better experimental conditions.

At the suggestion of the author, the correlation technique was used by Mr. J. E. Slosson (1950) in a Geological Survey study of modern sedimentation in New Mexico. Mr. Slosson wished to compute the textures of 205 samples, and tested 16 of these by a procedure similar to that outlined above. Mr. Slosson had to use an uncontrolled atmosphere, but as all of his measurements were made within 1 month, temperature and humidity undoubtedly varied much less than in the example cited above. He found that for his samples

$$(3) \qquad y = 1.72 + 11.24(P_w)$$

$$(4) \qquad z = 5.40 + 18.6(P_w)$$

in which y is as in equation (2), z is the per cent by weight of material finer than 50 microns, and P_w is the moisture content of the samples when unbagged after several months' storage in the laboratory. Mr. Slosson used the hydrometer method to determine y and z.

The reliabilities of equations (2), (3), and (4) are indicated in the following table:

TABLE 1

Area	Equation number	Independ. variable	Depend. variable	Standard error of estimate, per cent	Coefficient of correlation, per cent
Lake Mead	2	P_w	y	8.1	91.1
New Mexico	3	P_w	y	4.4	96.9
	4	P_w	z	8.1	97.3

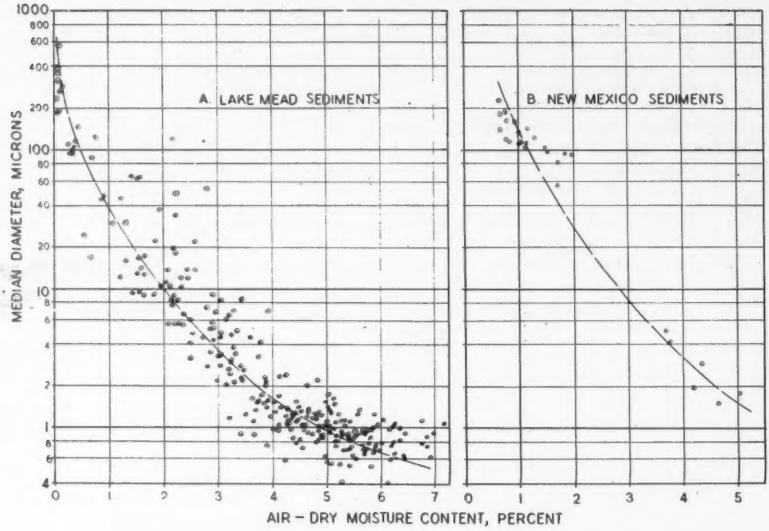


FIG. 1.—Air-dry moisture content as related to median diameter.

It appears from table 1 that the correlation for the Lake Mead samples suffers from the variations of temperature and humidity which were encountered. It is also of interest to consider the relationships between P_w and median diameter, which are presented graphically in figure 1.

In the case of the Lake Mead samples, considerable variation in the sorting coefficient resulted in a large degree of scatter when median diameter was plotted as a function of P_w. For this reason no correlation was calculated. Mr. Slosson's samples, being derived from two related rock types (Mesa Verde and Mancos formations), showed more uniformity in this respect; the absence of silt-size particles from those two formations made his data discontinuous. The data include some of his samples which were not used in the experimental correlation, but which were later analyzed after their moisture determinations, in combination with certain physiographic considerations, made these samples of special interest. The trend lines shown for both sets of data are intended to show only the general shape which an accurately determined curve would follow. The author believes that, for samples such as Mr. Slosson analyzed, it is possible to calculate median diameters from moisture determinations with considerable accuracy, particularly if the experimental methods and conditions are more closely controlled.

LIMITATIONS OF THE METHOD

Consideration of the foregoing data will show that the moisture content method of estimating texture will not be always advantageous. The method will save time only where large numbers of samples are involved, for the necessary experimental correlation will cancel any saving of time if the number of samples is small. The method is acceptable only if accuracy is not too important. It seems probable that the method would be most

useful in investigations of large numbers of samples whose textural parameters are to be considered statistically.

In addition, the technique will be satisfactory only if the experimental correlation yields sufficiently low standard errors of estimate and high correlation coefficients for the textural parameters most important to the study. If this condition is satisfied, much time may be saved as compared with more detailed methods.

In studies in which accuracy is of great importance, the moisture content method can be a valuable tool for preliminary investigation. For example, in the Lake Mead studies some 1300 samples were collected. All were analyzed for both initial and equilibrium moisture content, and the selection of the 273 which were analyzed by pipette was made partly on the basis of the equilibrium moisture contents.

REFERENCES

ARKIN, H., and COLTON, R. R., *1938. An outline of statistical methods:* 3d ed., Barnes & Noble, Inc., New York, pp. 77–92.

BODMAN, G. B., and MAHMUD, A. J., *1932.* The use of the moisture equivalent in the textural classification of soils: *Soil Science,* vol. 33, pp. 363–374.

BRIGGS, L. J., and MCLANE, J. W., *1907.* The moisture equivalent of soils: *U. S. Dept. Agriculture, Bur. of Soils Bull.* 45.

CASAGRANDE, A., *1934. Die Aräometer-Methode zur Bestimmung der Kornverteilung von Boden und andern Materialien:* Julius Springer, Berlin.

DAY, P. R., *1950.* Physical basis of particle size analysis by the hydrometer method: *Soil Science,* vol. 70, pp. 363–374.

ROBINSON, W. O., *1922.* The absorption of water by soil colloids: *Jour. Phys. Chem.,* vol. 26, pp. 647–653.

SLOSSON, J. E., *1950.* Sedimentation in area of diversion dam, Figuerado Wash, New Mexico: Unpubl. M.S. thesis, Univ. Southern Calif., Los Angeles, California.

VIEHMEYER, F. J., and HENDRICKSON, A. H., *1928.* Soil moisture at permanent wilting of plants: *Plant Physiology,* vol. 3, pp. 355–357.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 3, PP. 178–182
FIGS. 1–8, SEPTEMBER, 1951

DERIVATION OF A SIZE-FREQUENCY CURVE FROM THE CUMULATIVE CURVE

JAMES BUSH[1]
University of Washington, Seattle, Washington

ABSTRACT

A size-frequency curve is often convenient to use in conjunction with a cumulative curve in the analysis of a sediment. The sediment sample is run through a series of $\sqrt{2}$ sieves and the cumulative curve plotted from the obtained data by using standard techniques. The points of interest between the plotted points are then interpolated from the curve and the data used to plot a size-frequency curve. By this method a size-frequency curve can be drawn which favorably compares to one drawn from data determined by running the sediment through a more complete set of sieves. This method is very time-saving and sufficiently accurate, giving the desired information at any critical points of the size-frequency curve.

INTRODUCTION

In working with sediments it is often convenient to use a size-frequency curve in conjunction with the cumulative curve. Whereas more characteristics of the sediment can be obtained from the cumulative curve, the size-frequency curve readily shows the frequency distribution of the sediment. The cumulative curve can be drawn more accurately from a given datum than can the frequency curve. The cumulative curve is not affected by the chosen grade scale whereas the frequency curve is affected. Thus it is preferrable to derive the frequency curve from the cumulative curve rather than vice versa.

The method of arriving at the frequency curve as described in this article is both simple and rapid; the accuracy is determined by the accuracy in the drawing of the cumulative curve.

DISCUSSION

Table 1 gives the sieve analysis of a sediment from Biscayne Bay, Florida. The sample was first washed free of the common sea salts, then dried and weighed, after which it was shaken for fifteen minutes through a series of $\sqrt{2}$ sieves. The sediment remaining on each sieve was then weighed. Figure 1 is the cumulative curve plotted from the derived data. These same data are used to plot the frequency curve, figure 2. Figure 3 is a frequency curve plotted from the same data with the addition of the interpolated points derived from the cumulated curve, figure 1. Figures 4 through 8 show the resultant curves and a completely interpolated curve of another sample which was run through the $\sqrt{2}$ and $\sqrt[4]{2}$ sieves. It will be observed that the interpolated curve, figure 7, closely approximates the curve shown in figures 8, which was the same sample but was run through the $\sqrt[4]{2}$ instead of $\sqrt{2}$ sieves. The curve plotted from the $\sqrt[4]{2}$ sieve data was used as a check against the interpolated curve.

METHOD

In order to interpolate points from a cumulative curve for the determination of the frequency curve, it is first necessary to draw the cumulative curve. Table 1 lists the data for a typical sample whose cumulative curve is drawn in figure 1 on a semi-logarithmic scale. The size-frequency curve may now also be plotted from these same data (fig. 2).

It is seen from the size-frequency curve (fig. 2) that the points of interest lie

[1] The author wishes to thank Marion Bush, his wife, for helpful criticism and editing of the paper.

TABLE 1.—*Analysis of a typical sediment.*

ϕ	Mesh	Mm	Weight	Percentage	Cumulative percentage
−2.0	5	4.00	0.1027	0.204	0.204
−1.5	7	2.83	0.3118	0.620	0.824
−1.0	10	2.00	0.3531	0.702	1.526
−0.5	14	1.41	0.6095	1.212	2.738
0.0	18	1.00	1.4046	2.794	5.532
0.5	25	0.707	1.9282	3.835	9.367
1.0	35	0.500	3.1388	6.243	15.610
1.5	45	0.354	5.3412	10.623	26.233
2.0	60	0.250	10.3223	20.530	46.763
2.5	80	0.177	14.3014	28.444	75.207
3.0	120	0.125	10.7227	21.326	96.533
3.5	170	0.088	1.2427	2.472	99.005
4.0	230	0.062	0.1361	0.271	99.276

between the diameters 0.088 and 0.250 mm. It is in this range that more detailed data are desired in order to determine the approximate location of the peak of the curve as well as the slopes, especially between the diameters 0.088 and 0.125 mm. It is now necessary to determine the values for the points between the sieve diameters.

As an example, a value for the point with a diameter of 0.149 mm will be determined. This diameter is one-fourth of a phi unit to the right of 0.177 mm and equally spaced from 0.125 mm. It is, therefore, a diameter for which data would have been determined if the $\sqrt[4]{2}$ sieves had been used.

From the cumulative curve (fig. 1) the percentage of grains with diameters larger than 0.149 mm is determined. In this example it is 90.4 per cent. Next, the per cent of sediment that has a diameter larger than the size half-way between the diameters 0.177 and 0.250 mm is determined, in this case a diameter of 0.210 mm. The value at this diameter is 60.3 per cent. This latter value is subtracted from the value determined for the diameter at 0.149 mm. The difference, 30.1 per cent, represents the per

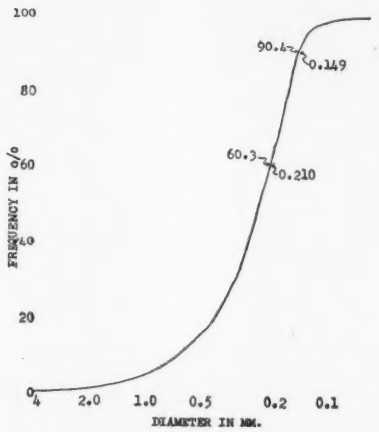


FIG. 1.—Cumulative curve of a typical sediment as listed in table 1.

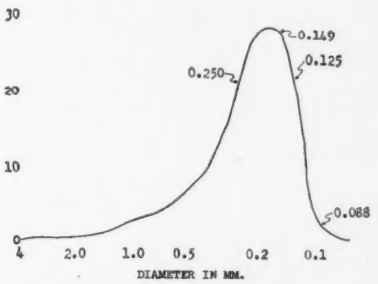


FIG. 2.—Size-frequency curve of typical sample shown in figure 1.

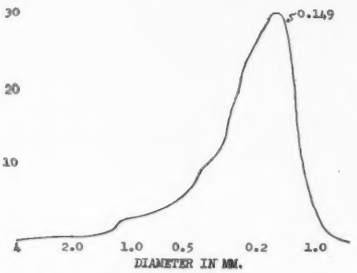


FIG. 3.—Interpolated size-frequency curve of sample shown in figures 1 and 2.

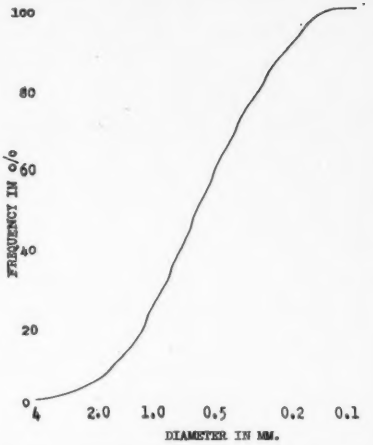


FIG. 4.—Cumulative curve drawn from data obtained by using a series of $\sqrt{2}$ sieves.

cent of sediment which has a diameter larger than 0.149 mm, but smaller than 0.210 mm. This value, 30.1 per cent, is plotted on the size-frequency chart at the diameter 0.149 and the curve drawn through this point. This procedure is repeated for the determination of the value at the diameter 0.105 mm. In this case, the per cent of sediment which is greater than the diameter 0.149 mm is determined, 90.4 per cent, and subtracted from the per cent of sediment which has a diameter greater than 0.105 mm, 98.2 per cent. This gives a difference of 7.8 per cent. This value is also plotted on the size-frequency chart and the curve drawn through the point.

It is necessary, when determining a value for any diameter, to select the correct diameters for which the percentages are determined from the cumulative curve. If the sediment was sieved through a series of $\sqrt{2}$ sieves, then the values of the two points read from the cumulative curve must be the same horizontal distance apart on the graph as are two sieve diameters, that is half of a phi unit distance or half of a Wentworth distance. If the $\sqrt[4]{2}$ sieves were used, the horizontal distance between the two points must be one-fourth of a phi unit apart or the same horizontal distance apart as are two successive sieve sizes.

Thus, it can be seen that the value of the point to be determined does not necessarily have to be half-way between two empirically determined points, but can be located anywhere between the two. Of greater importance is the fact that the other point, for which the value is determined from the cumulative curve, must be a definite distance to the left, having a larger diameter, of the point of interest.

The curve for figure 4 was drawn from data found by running a sample of sediment through a series of $\sqrt{2}$ sieves. Figure 6 is the size-frequency curve drawn from these data. The same sediment was also run through a series of $\sqrt[4]{2}$ sieves; the data were used in the drawing of figures 5 and 8. A curve, figure 7, was then drawn from interpolated data derived from the cumulative curve, shown in figure 4. This interpolated curve compares more favorably with that shown in figure 8 than does the curve shown in figure 6. Table 2 lists the data from which figure 7 was drawn. These data are comparable in percentage to those which would be derived from a series of $\sqrt[4]{2}$ sieves, rather than those of $\sqrt{2}$ sieves. In other words, the per cent of sediment theoretically determined for each sieve is approximately equivalent

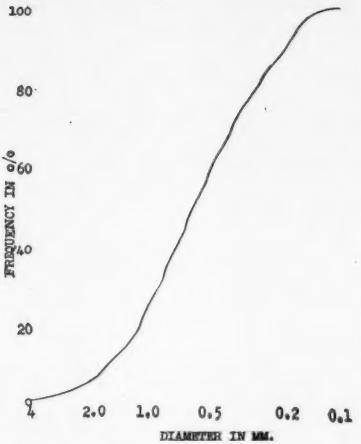


FIG. 5.—Cumulative curve drawn for same sample as used in figure 4, but data obtained by using a series of $\sqrt[4]{2}$ sieves.

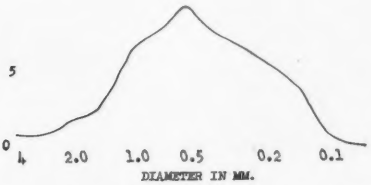


FIG. 6.—Size-frequency curve drawn from same data as used for figure 4.

in percentage to that which would be found on a series of $\sqrt[4]{2}$ sieves, rather than that for the interpolated and determined sizes in a $\sqrt{2}$ series.

The above described method has been used by the author for the determination of many points from cumulative curves. The interpolated curve is a more exact representation of the size-frequency distribution of the sediment than is the noninterpolated curve. This is readily demonstrated by figures 4 through 8.

The reader may not agree with the author's basic assumption that the cumulative curve can be drawn more ac-

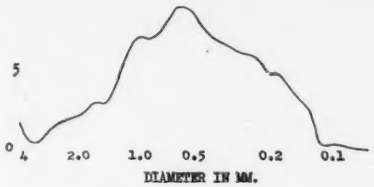


FIG. 7.—Interpolated size-frequency curve determined from cumulative curve of figure 4, which data are listed as table 2.

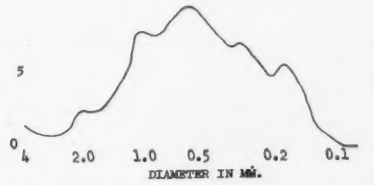


FIG. 8.—Size-frequency curve drawn from same data as used for figure 5.

TABLE 2.—*Data interpolated from figure 4.*

ϕ	Mesh	Mm	Cumulative percentage	Percentage
−2.0	5	4.00	1.7	1.7
−1.75	6	3.36	2.2	0.5
−1.50	7	2.83	3.5	1.3
−1.25	8	2.38	5.2	1.7
−1.00	10	2.00	7.3	2.1
−0.75	12	1.68	10.1	2.8
−0.50	14	1.41	13.1	3.0
−0.25	16	1.19	18.0	4.9
0.00	18	1.00	25.2	7.2
0.25	20	0.840	32.4	7.2
0.50	25	0.707	40.2	7.8
0.75	30	0.595	49.2	9.0
1.00	35	0.500	57.8	8.6
1.25	40	0.420	65.2	7.4
1.50	45	0.354	72.0	6.8
1.75	50	0.297	78.3	6.3
2.00	60	0.250	84.3	6.0
2.25	70	0.210	89.4	5.1
2.50	80	0.177	94.2	4.8
2.75	100	0.149	97.8	3.6
3.00	120	0.125	100.3	2.5
3.25	140	0.105	100.7	0.4
3.50	170	0.088	101.1	0.4
3.75	200	0.074	101.3	0.2
4.00	230	0.062	101.5	0.2

curately from a given datum than can the frequency curve. If the antithesis of this is assumed, the cumulative curve can readily be corrected from the size-frequency curve.

The method is rapid and has been found to be sufficiently accurate so that it is generally only necessary to run a sample through a series of $\sqrt{2}$ sieves instead of the more time-consuming series of $\sqrt[4]{2}$ sieves.

It is true that the process outlined above attempts to obtain more accurate data from the cumulative curve than are actually used in the plotting of this curve. However, it is believed that by drawing the cumulative curve to the best of one's ability, it is possible thereby to derive a usable size-frequency curve. This curve is more accurate than one that can be drawn from the original data. This is especially true for that portion of the cumulative curve which approaches a straight line (or that having the larger radius of curvature), and more true for the major portion of the cumulative curve when it is drawn on probability paper.

REFERENCES

BROTHERHOOD, G. R., and GRIFFITHS, J. C., *1947*. Mathematical derivation of the unique frequency curve: *Jour. Sedimentary Petrology*, vol. 17, pp. 77–82.

CAMP, B. H., *1931*. *The mathematical part of elementary statistics:* New York.

KRUMBEIN, W. C., *1934*. Size frequency distributions of sediments: *Jour. Sedimentary Petrology*, vol. 4, pp. 65–77.

———, *1936*. Application of logarithmic moments to size frequency distribution of sediments: *Jour. Sedimentary Petrology*, vol. 6, pp. 35–47.

———, *1936*. Rejoinder to Wentworth's discussion of the method of moments: *Jour. Sedimentary Petrology*, vol. 6, pp. 159–160.

———, *1938*. Size frequency distribution of sediments and the normal phi curve: *Jour. Sedimentary Petrology*, vol. 8, pp. 84–90.

———, and PETTIJOHN, F. J., *1938*. *Manual of Sedimentary Petrography:* D. Appleton-Century Co., New York, 549 pp.

MILLS, F. C., *1924*. *Statistical methods:* New York.

OTTO, G. H., *1939*. A modified logarithmic probability graph for the interpretation of mechanical analysis of sediments: *Jour. Sedimentary Petrology*, vol. 9, pp. 62–76.

WENTWORTH, C. K., *1929*. Method of computing mechanical composition types in sediments: *Geol. Soc. America Bull.*, vol. 40, pp. 771–790.

———, *1936*. The method of moments: *Jour. Sedimentary Petrology*, vol. 6, p. 158.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 3, PP. 183–184
SEPTEMBER, 1951

DISCUSSION

SOME REMARKS ON THE MINERAL EPIDOTE IN CONNECTION WITH THE LOESS PROBLEM

A reply to D. J. Doeglas, "Loess, an eolian product"

F. F. F. E. VAN RUMMELEN[1]
University of Indonesia, Bogor, Indonesia

In the paper, "Loess, an eolian product," Doeglas (1949) compares the "loess" of southern Limburg (the Netherlands) with loess-products of the Mississippi Valley. Van Rummelen, Sr. (1950) has disputed the views of Doeglas, but has not presented quantitative results of a conclusive nature concerning the epidote content of "loess."

The present author has no intention of going into the problem of genesis of the loessoïdes of Limburg. That matter has been the subject of many publications by van Rummelen, Sr. However, one of the basic arguments in the problem has been that of high epidote percentage. Van Rummelen, Sr., not being a mineralogist, has not been able to answer such arguments. The high epidote percentage in loess is a fact not in dispute.

Doeglas uses the high epidote percentage to prove that loess could not be derived locally, from older sediments. His table 1 is presented in an attempt to prove that the Cretaceous, Oligocene, Miocene, and Pliocene contain practically no epidote, whereas loess contains a high percentage. If true, the theory of van Rummelen, Sr., is contradicted, and the theory of eolian-glacial origin, as advocated by Doeglas, appears more reasonable. The views of Doeglas, as presented in his table 1, gives basis for a belief that van Rummelen, Sr., lacks factual support for his theory of loess origin.

No evidence was presented by Doeglas as to the number of samples upon which the idea was advanced that the Cretaceous and Tertiary formations lack epidote. That the notion is incorrect is hereby presented on the basis of 751 samples, all of which were analyzed mineralogically by the author and others. The present author has analyzed more samples than any previous worker in the Netherlands. Epidote percentages were determined, in the heavy mineral content, and were averaged by formations, with the following result:

TABLE 1

Formation age	Epidote percentage	Number of samples
Amstelian	0.9	119
Poederlian	2	127
Upper Diestian	2	114
Middle Diestian	11	20
Lower Diestian	1	41
Upper Miocene	22	11
Middle Miocene	6	41
Braunkohlform.	10	7
Upper Oligocene	14	60
Middle Oligocene	9	162
Lower Oligocene	24	48
Maestrichtian	14	1

The mean value for the terrestrial Pliocene is 5 per cent, based on 421 samples.

[1] This paper has been edited by R. J. Russell. Although the exact wording is not that of the author, the factual data and general character of discussion are accurately presented. J.L.H.

A comparison of values with those of Doeglas is given below:

TABLE 2

Age	Epidote percentage	
	Doeglas (1949)	Various authors
Pliocene	2	5
Miocene	—	13
Oligocene	—	16
Maestrichtian	—	14

It is impossible to accept the interpretations of Doeglas. They must be based either upon too few samples or else upon selected samples. The mean values of epidote percentages based on the work of the author and others is entirely objective. Doeglas' statement that the Tertiary formations of Limburg are deficient in epidote is incorrect. Both hornblende and garnet are also present in those formations.

There is, therefore, no reason at all for believing that the loessoïdes of Limburg could not have been derived from Tertiary formations present in the region.

REFERENCES

DOEGLAS, D. J., *1949*. Loess, an eolian product: *Jour. Sedimentary Petrology*, vol. 19, pp. 122–117.

MULLER, J. E., *1943*. Sedimentpetrologie van het dekgebergte in Limburg: *Med. Geol. Stichting*, serie C-II-2-2.

VAN RUMMELEN, F. F. F. E., *1950*. Plioceen in Zuid- en Midden Limburg (manuscript).

VAN RUMMELEN, F. H., *1950*. Erratica in de loessoïden van Ransdaal (met medewerking van F. F. F. E. van Rummelen): *Nat. Hist. Maandbl.* 39e, Jrg. no. 5-6-7-8.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 21, NO. 3, P. 185
SEPTEMBER, 1951

REMARKS ON "BEACH SANDS OF THE MEDITERRANEAN COAST OF EGYPT" BY MOHAMED E. HILMY

N. M. SHUKRI
Fouad I University, Cairo, Egypt

The following remarks concern the paper by Mohamed E. Hilmy on "Beach Sands of the Mediterranean Coast of Egypt," *Jour. of Sedimentary Petrology*, vol. 21, pp. 109–120, 1951.

"I wish to direct the attention of Mr. Hilmy that the black sands of Rosetta were mentioned in a previous publication (N. M. Shukri, The mineralogy of some Nile sediments. *Quart. Jour. Geol. Soc. London*, cv, p. 522 and fig. 1, 1950, also discussion by Dr. C. F. Davidson, *ibid.*, pp. 533–534). Davidson states, among other remarks of considerable interest, that "at a conservative estimate the extent of these crude black sand deposits, considering the relatively high grade occurrence alone, is not less than 5,000,000 tons."

Mr. Hilmy's remarks on the persistence of the unstable minerals during transportation by the Nile and of the minor addition of material from other rocks along the course of the river (p. 118) have been also previously discussed (N. M. Shukri, *op. cit.*, and the discussion that followed the reading of the paper, *Proc. Geol. Soc. London*, No. 1449, 62–65, April 1949, also N. M. Shukri, *Geol. Mag.*, lxxxii, p. 32, 1945, the last reference is given by Mr. Hilmy himself). The discussion of the Nile sediments was based on the examination of a large number of samples (over 150) along the course of the river from near its sources to the Mediterranean coast.

The huge amounts (some 55 million tons) of Abyssinian sands, silts and muds carried annually by the Nile into the Mediterranean during flood time are distributed by the general eastward sea currents towards Rafah. It is a well known fact that during flood time the sediments of the Nile change the colour of the sea for many kilometers off shore. Parts of the beaches east of the delta, e.g. Port Said, and between the two branches of the river receive great amounts of the mud and silt of the Nile (owing to the eastward current) whereas the beaches west of the delta away from Rosetta, e.g. Alexandria, are "cleaner" during flood time and receive but little of the Nile sediments."

TURBIDITY CURRENTS
AND
THE TRANSPORTATION OF COARSE SEDIMENTS
TO DEEP WATER

A Symposium Sponsored by the Society of Economic Paleontologists and Mineralogists

CONTENTS

Foreword ..... *R. Dana Russell*
Applications of hydraulics to the study of marine turbidity currents ..... *H. W. Menard and J. C. Ludwick*
Properties of turbidity currents of high density ..... *Ph. H. Kuenen*
Some quantitative aspects of Lake Mead turbidity currents ..... *Howard R. Gould*
Transportation of sand into deep water ..... *Francis P. Shepard*
Displaced Foraminifera faunas ..... *Fred B. Phleger*
Sedimentary history of the Ventura Basin, California, and the action of turbidity currents ..... *M. L. Natland and Ph. H. Kuenen*

To be published as Special Publication No. 2 of the S. E. P. M. about October 1, 1951. Style and format similar to that of the *Journal of Sedimentary Petrology*. Approximately 112 pp., 61 illustrations. This publication will be sold at the following prices:

Advance sale to S. E. P. M. members	$2.00
Post-publication sale to S. E. P. M. members	2.25
Advance sale to non-members of S. E. P. M.	2.50
Post-publication sale to non-members of S. E. P. M.	2.75

In order to obtain this publication at the pre-publication price, an order accompanied by remittance must be sent in before October 15, 1951. The order form at the bottom of the page may be used. Please place order at your earliest convenience so that we may better judge the size of the edition to be printed. *Make checks payable to the Society of Economic Paleontologists and Mineralogists.* Please note that *subscribers* to the Journals are not *members* of the Society. Only *members* may obtain the symposium at the rates for members.

ORDER FORM

To: Society of Economic Paleontologists and Mineralogists
Box 979, Tulsa 1, Oklahoma

Please send me, when published, ... copies of the symposium, "Turbidity Currents and the Transportation of Coarse Sediments to Deep Water."

I enclose remittance in the amount of $..... ($2.00 per copy, advance sale to members; $2.50 per copy, advance sale to non-members).

Name (printed) .....
Address .....
.....
.....
.....

Special Sale

JOURNAL OF PALEONTOLOGY

VOLUME I (1927), REPRINTED 1948

The Society of Economic Paleontologists and Mineralogists announces a special sale of Volume I of the JOURNAL OF PALEONTOLOGY for a limited time only. This reprinted volume, consisting of more than 300 pages of text and line figures and 49 half-tone plates, contains papers on Foraminifera, Ostracoda, Diatomacea, Cephalopoda, and other fossils—as well as articles on correlation, stratigraphy, and sedimentology.

You can now, and for a LIMITED TIME, get Volume I for a fraction of the price of a current subscription. Send for your copy today.

SPECIAL PRICE, POSTPAID

$3.50 in paper cover. **$4.00, clothbound**

Orders should be addressed to:

THE SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
Box 979, Tulsa 1, Oklahoma

Diatoms of Historic Importance

One of the world's outstanding private collections of diatoms, formerly the property of J. R. Bartholomew, Research Associate of the Farlow Herbarium, Harvard University, is now available through Ward's to the world of science at large. Consisting of material taken from more than a thousand different collections and cleanings, made during a period of over one hundred years, the collection embraces numerous localities represented in Tempere and Paragallo "Diatomées du Monde Entier." Many of the specimens came from the original collections of such prominent workers as W. A. Terry, James Smith, R. D. Nevius, H. H. Gran, and V. L. Eardley-Wilmot, among others. Specimens which are of historic interest are being provided on microscope slides, while the remainder are available in bulk form. *A list of individual offerings is available on request.*

WARD'S NATURAL SCIENCE ESTABLISHMENT, INC.

3000 RIDGE ROAD EAST · ROCHESTER 9, N.Y.

Oceanographic Instruments

***SONIC SEDIMENTATION SAMPLERS, as designed by LaFond, Dietz, and Knaus.
***MECHANICAL SEDIMENTATION SAMPLERS, all patterns, "Scoopfish" or Underway Sampler, cup type; Deep Sea Grab Sampler, Snapper type; Standard Snapper Samplers; Sediment Coring Devices, for cores 6" to 12';
***DREDGES, hand and power types, with removable sieves
***DEEP SEA REVERSING THERMOMETERS, all models
***REVERSING WATER BOTTLES
***CURRENT METERS, Mechanical and Electronic types
***WINCHES, Oceanographic, Hand and Power types
***UNDERWATER CAMERAS, for Lakes and Oceans
***PORTABLE TEMPERATURE RECORDERS, self contained
***ELECTRONIC TEMPERATURE, CONDUCTIVITY, and DEPTH RECORDER
***MULTI CHANNEL TEMPERATURE RECORDING SYSTEMS (from 1 to 16 Stations)
***FLOW METERS FOR LARGE PLANKTON NETS
***METER WHEELS, all types, in Meters, Feet and Fathoms
***PLANKTON NETS, all sizes
***PLANKTON SAMPLERS
***OCEANOGRAPHIC WIRE, Galvanized, Stainless Steel & Nylon coated

We have established an international reputation as developers and fabricators of quality instruments for oceanographic research. Our glassblowing and electronic laboratories are staffed by a well qualified scientific and technical staff.

KAHL SCIENTIFIC INSTRUMENT CORP.
P.O. BOX 1166 EL CAJON (SAN DIEGO) CALIF.
Eastern Office: 50 West 3 St., New York 12, N.Y.

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

SOCIETY OFFICERS (APRIL 1951-MARCH 1952)

President: THOMAS H. PHILPOTT, Shreveport, Louisiana

First Past-President: WILLIAM C. KRUMBEIN, Evanston, Illinois

Second Past-President: H. B. STENZEL, Austin, Texas

Vice-President: KENNETH O. EMERY, Los Angeles, California

Secretary-Treasurer: CECIL G. LALICKER, Dept. of Geology, University of Kansas, Lawrence, Kansas

Editor: J. L. HOUGH, University of Illinois, Urbana, Illinois

Consulting Editor: W. H. TWENHOFEL, Orlando, Florida

PACIFIC SECTION OFFICERS (1950–1951)

President: LOUIS J. SIMON, Los Angeles, California

Secretary-Treasurer: DOUGLAS CRAWFORD, Compton, California

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

ASSOCIATION OFFICERS (APRIL 1951-MARCH 1952)

President: FRANK A. MORGAN, Los Angeles, California

Past-President: C. L. MOODY, Shreveport, Louisiana

Vice-President: L. G. Weeks, New York, New York

Secretary-Treasurer: ROBERT H. DOTT, Oklahoma Geological Survey, Norman, Oklahoma

Editor: KENNETH K. LANDES, Ann Arbor, Michigan

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN